Continuing the Development of a Physics-Based Weight (PBWeight) Prediction Tool for Conceptual Design: Build 1

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I. Introduction

Many critical challenges currently exist for designing, developing, and analyzing physics-based conceptual aircraft design tools. Often engineers struggle with determining the appropriate levels of fidelity in models or techniques (e.g. reduced order) to be used in the conceptual design phase. One challenge of particular relevance to the current effort is the desire to accurately and efficiently predict weights and loadings for unconventional designs. Unconventional designs are required to break through the common or 'expected' limitations associated with conventional designs. Furthermore, the ability to assess, in a rapid manner, the feasibility of these unconventional designs is crucial to NASA's Environmentally Responsible Aviation (ERA) project as well as many other efforts seeking to develop enabling technologies required to solve a variety of important design problems (high lift-to-drag ratios, community noise, reduced drag, etc.). The Blended Wing Body (BWB) or Hybrid Wing Body (HWB) aircraft, for example, has been researched and analyzed for many years as an unconventional efficient transport configuration.

Approaches for weight prediction in the conceptual design phase typically consist of parametric relations or empirical databases (Ref. 1) (Ref. 2). Historical databases work reasonably well when applied to existing or conventional designs, however, they fail to predict accurately the weights and loads associated with unconventional designs (like the BWB). There exists a need to augment existing historical databases with a physics-based methodology/capability for predicting the weights and loads of unconventional designs.

In the current effort, M4 Engineering has further developed the PBWeight software to provide a tool to create meta-geometry definitions of internal structure rapidly. The main goal for this effort was to develop a software tool capable of generating weight and load responses for unconventional designs from physics-based simulations. In an effort to minimize risk and expedite development, the PBWeight software utilizes OpenVSP, an open source parametric aircraft geometry tool, as well as a previously developed tool (RapidFEM) to automatically generate geometry and Finite Element Models (FEMs) of complex built-up structures for rapid concept evaluation and structural optimization. The PBWeight software allows a user to specify conceptual design-level information about wing and fuselage structures using OpenVSP, then automatically create FEMs suitable for optimization and generate comprehensive weight statements.

The main objective of this paper is to demonstrate the effectiveness of the PBWeight software tools to create an efficient and user-friendly interface for streamlining the internal structural layout process, assigning material properties, attachments, loads, and optimization analysis information. Evidence will be provided that demonstrates a considerable speed up in time required to create component FEMs for the MD-87 example compared to the time required during the Phase I effort (Ref. 3).

In the following section, a brief overview of the PBWeight process work flow is given. In Section III, a description of the development of the PBWeight GUI and integration within OpenVSP is given. In Section IV, a demonstration of the PBWeight Tool on the MD-87 configuration is provided. In Section V, the example problem description will be described in detail. Finally, in Section VI, the main objectives of our future work will be given.

II. PBWeight Process Work Flow Overview

There are four main steps involved for producing an optimized weight statement using the PBWeight software suite. The PBWeight software work flow can be seen in Figure 1. An overview of the PBWeight process are shown below followed by a detailed description of each step:

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PBWeight Process Work Flow Summary

1. Place RapidFEM Sketch Points (these are the points that will connect internal structural entities as well as boundaries) on each geometry component.
2. Specify RapidFEM Explicit Sketch Cards in order to “build up” the internal structure, assign property regions, non-structural mass attachments, mesh properties, and analysis deck information.
3. Merge and trim component FEMs.
4. Perform weight optimization analysis (including static aeroelastic analyses, flutter, etc.) to size aircraft and generate weight statement.

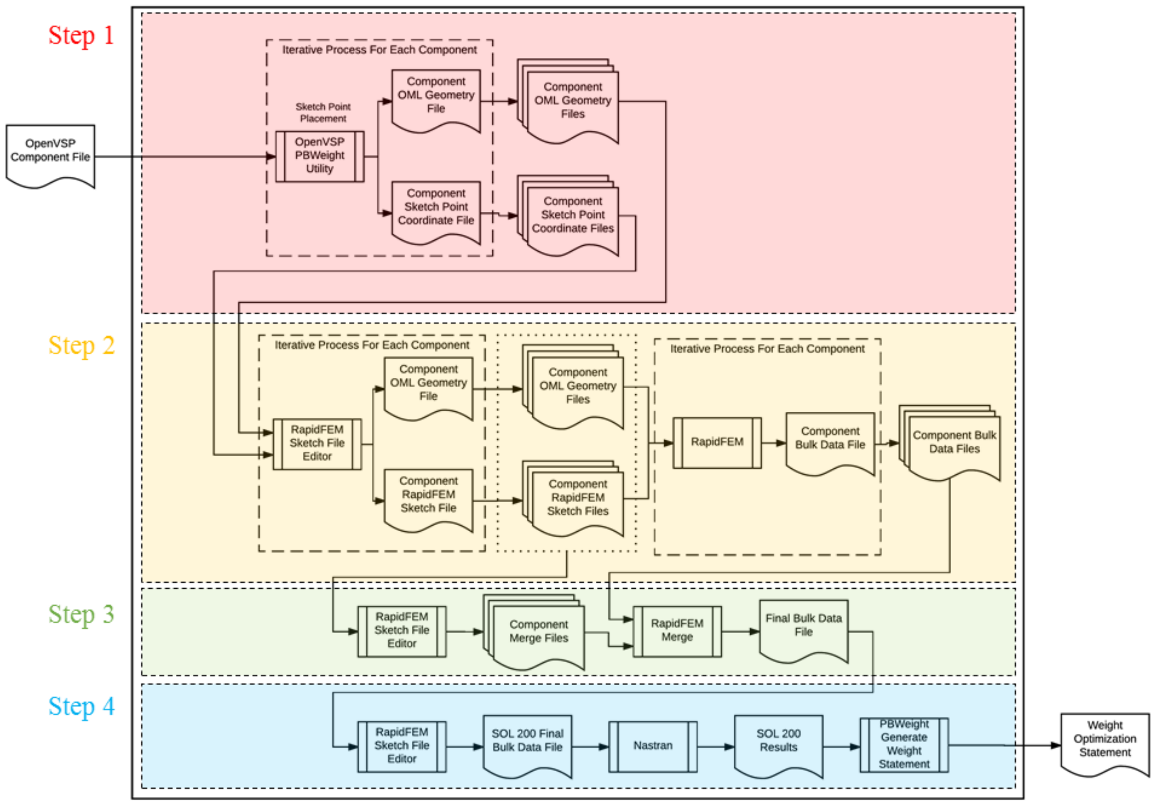


Figure 1: PBWeight Software Work Flow.

The first step in the process is to create a Sketch Point Layout for each component containing internal structure using the PBWeight Utilities developed within OpenVSP. For example, the Sketch Point Layout Creator Tool allows a user to attach Sketch Points to the surface of an OpenVSP component, such as a wing or a fuselage. These Sketch Points share a parent/child relationship that keeps them attached to the parent component, which is particularly important when design parameters change after Sketch Points have been placed. By leveraging this parent/child component relationship, the previously placed points move accordingly when the parent component geometry is altered. Once the Sketch Points are properly placed, the user must build up the internal structure (i.e. define ribs/spars, skins, attachments, etc.) by utilizing the RapidFEM Sketch File Editor.

The second step in the PBWeight process is to create RapidFEM explicit sketch cards used to define internal structure, such as BEAMs and SKINs, using the RapidFEM Sketch File Editor. After the meta-geometry definitions have been created, the RapidFEM Sketch File and STL for each component are used as inputs for RapidFEM, which will produce component FEMs.

After a complete set of component FEMs have been produced by RapidFEM, the third step in the PBWeight process is to Merge/Trim the individual components into a final FEM representing the entire vehicle. The desired Merge/Trim locations are designated by specifying a set of precise property regions. Once the Merge/Trim regions are created, RapidFEM will process these regions through an iterative procedure and produce a final completely merged and trimmed FEM.

After analyzing a variety of important load cases (static aeroelastic, flutter, etc.) to properly size the aircraft components and validate the design, the last step in the PBWeight process is to run Nastran Solution 200 to produce the optimized weight statement. From the PBWeight dropdown menu, the user selects “Generate Weight Statement” and a weight statement detailing individual component weights is displayed.

III. Development of PBWeight GUI and Integration within OpenVSP

The goal for the PBWeight GUI software is to provide a natural extension to OpenVSP for allowing users to create meta-geometry definitions of internal structure rapidly. The PBWeight GUI software has been developed to support version 3.5.0 of OpenVSP and was successfully built from source code obtained from OpenVSP’s GitHub repository. OpenVSP is constantly being improved to increase functionality and robustness, thus an approach has been taken within the PBWeight GUI development to promote ease of version upgrading. This will not only ensure the PBWeight GUI will have access to the new functionality within OpenVSP as its software progresses, but it will also ensure that the PBWeight GUI will be compatible with an up-to-date version of OpenVSP.

A. PBWeight GUI Integration within OpenVSP

Development of the PBWeight graphical user interface will be consistent with the current OpenVSP source code, while the core PBWeight analysis software will be separate and callable from the PBWeight dropdown menu and from the RapidFEM Sketch File Editor. Integration began with the creation of a PBWeight dropdown menu on OpenVSP’s main window as shown in Figure 2. This dropdown menu gives the user access to the PBWeight specific toolset, which includes a Sketch Point Layout Creator, the RapidFEM Sketch File Editor, as well as a Weight Statement Utility tool.

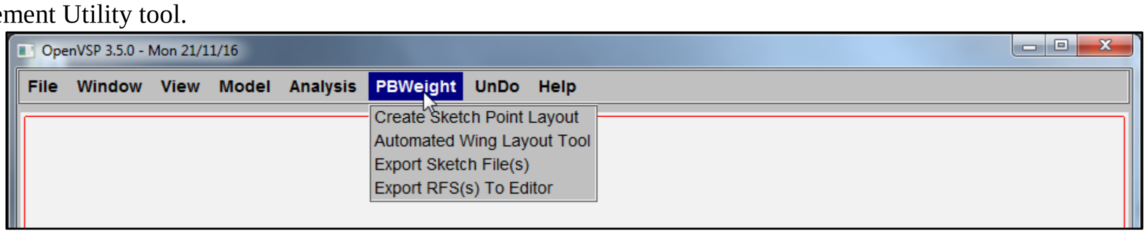


Figure 2: PBWeight Dropdown Menu.

A Sketch Point Layout Tool was created to attach a Sketch Point Layout to a geometry component, and allows the user to place Sketch Points onto the component. The two main methods for placing Sketch Points are by placing one point at a time, or placing multiple points at once.

Before placing points, the sketch plane orientation needs to be specified by selecting one of the three principle planes (XY, XZ, and YZ) located at the top of the Sketch Point Layout Tool. The first placement method offered by the tool is the single point placement method as seen in Figure 3 below. To properly position a Sketch Point, the provided UW sliders are used, which is very similar to the method employed by OpenVSP for traversing Blank geometry components across other component surfaces. X, Y, and Z coordinate indicators are provided to the user and are updated as the Sketch Point moves along the component surface.

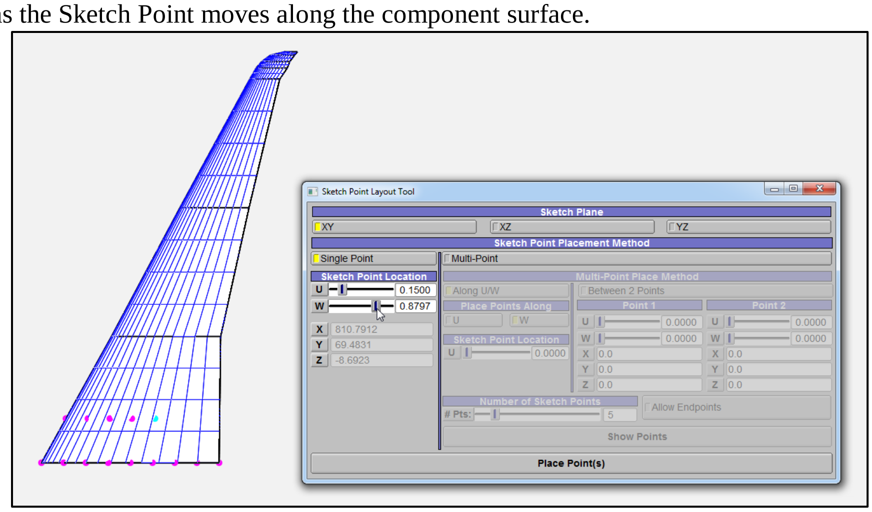


Figure 3: Sketch Point Layout Tool – Single Point Placement Method.

Multi-point placement is the second Sketch Point placement method offered by the Sketch Point Layout Tool as seen in Figure 4. When this method is selected, a red line appears onto the component's surface which represent where the points will be placed. The user is able to select the location of where the points will be placed as well as how many points will be placed at once. Once these settings are applied and the Show Points button is pressed, the placement line is replaced with equidistantly placed Sketch Points. At this point, the Sketch Points are temporarily placed, allowing the user to further refine the location of the points. Once the Place Point(s) button is pressed, these Sketch Point are placed in the Sketch Point Layout and the process starts over for the next set of points.

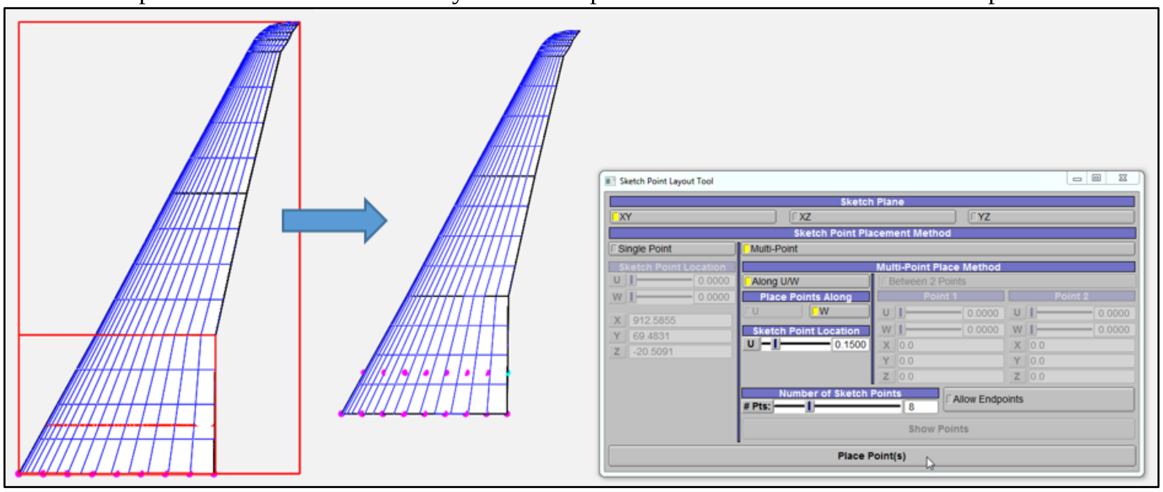


Figure 4: Sketch Point Layout Tool – Multi-Point Placement Method.

Initially, pre-existing "Blank" geometry objects were used as placeholders for sketch points due to their connectedness (e.g. "Blank" objects can be set as child components and mapped to the geometric surface through UW-mapping) to the actual geometric entity and underlying data structure. It is important to note that this enabled the development team to leverage existing capabilities (e.g. linked to parent geometry if parameters are changed, coordinate transformations for point location, etc.) inherent to the "Blank" geometry object. The custom Sketch Point Layout Tool was capable of placing "Blank" geometry objects using the "Place Point(s)" button; however, since the existing OpenVSP source code protects "Blank" parameters, it would be impossible to modify them using the custom tool in a robust and efficient manner. Therefore, two custom geometry objects were developed to allow the Sketch Point Layout Tool full access to the object parameters.

One of the two custom created geometry types is the Sketch Point Layout. This geometry entity is essentially a container for the custom-made Sketch Point geometry objects. The Sketch Point Layout attaches directly to the OpenVSP geometry component. The second custom made geometry is the Sketch Point. Sketch Points attach directly to the OpenVSP geometry component containing a Sketch Point Layout. This attachment to the parent geometry is very important as it ensures the Sketch Point is always within the bounds of the parent geometry. The actual Sketch Point entities are hidden in the main Geometry tree hierarchy window to prevent clutter. An additional window to manage Sketch Points was created and can be accessed by selecting the Sketch Point Layout geometry object, as seen in Figure 5. The suppression of Sketch Points listing within the OpenVSP geometry browser was to keep the existing geometry browser manageable, to keep the PBWeight specific geometry entities more isolated from the existing OpenVSP geometry entities, and lastly, to create a more intuitive way of accessing and modifying Sketch Point Layouts. This separation also alleviates problems brought on by the current hierarchical ordering scheme when Sketch Points were attached to an OpenVSP geometry entity.

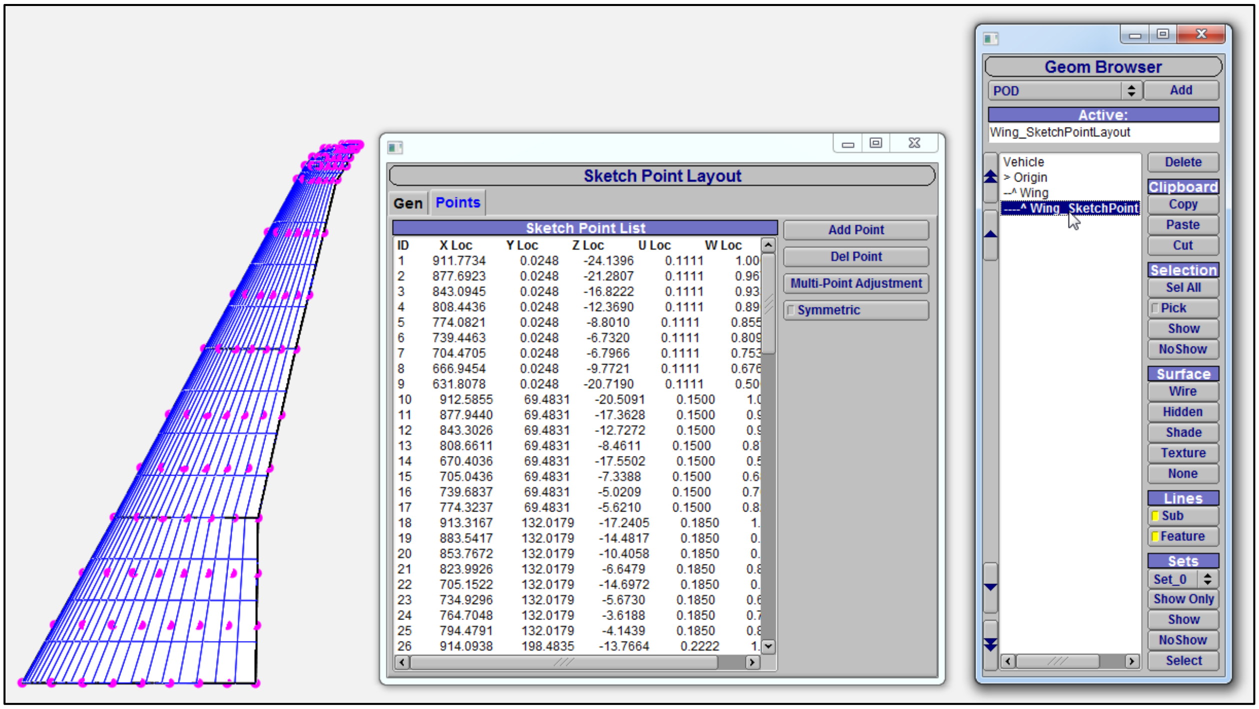


Figure 5: Sketch Point Layout Point Browser.

The Sketch Point Layout Point Browser displays all the Sketch Points associated with the selected layout and allows the user to add additional points, delete points, adjust the position of existing points, and export a basic RapidFEM Sketch file containing Sketch Point coordinate data.

To better increase the ease of use during the Sketch Point Layout creation process, a Multi-Point Adjustment Tool was created. This tool gives the user the ability to modify the position of multiple points at once, using two different methods. First, points that need to be moved are CTRL selected in the Sketch Point Layout Browser. By pressing the Multi-Point Adjust button, the Sketch Point Adjustment Tool screen opens. The first method the tool offers is the Multi-Point Traverse method as seen in Figure 6. As the UW sliders are moved, a delta is applied to the UW coordinates of all selected points. This allows the Sketch Points to maintain their original position relative to the other selected points.

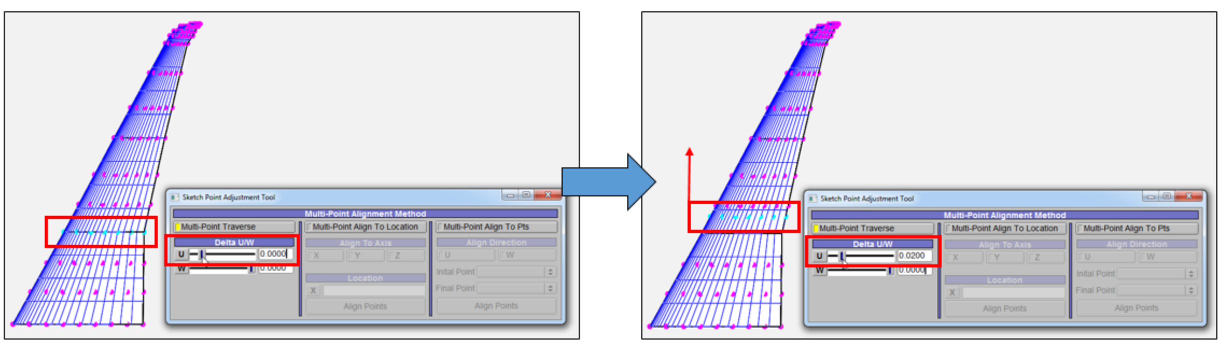


Figure 6: Sketch Point Adjustment Tool - Multi-Point Traverse Method.

The second method is the Multi-Point Align to Location method. This method aligns all the selected Sketch Points to a specified X, Y, or Z (depending on the component and sketch plane orientation) location on the component's surface as seen in Figure 7.

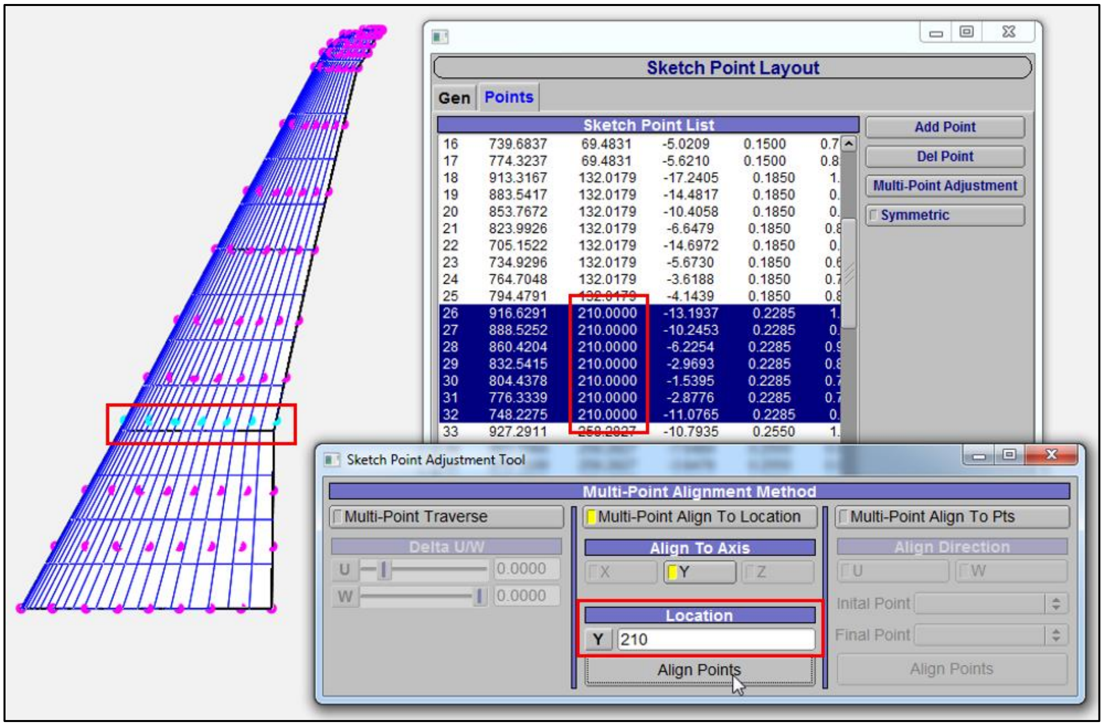


Figure 7: Sketch Point Adjustment Tool - Multi-Point Align to Location Method.

B. RapidFEM Sketch File Editor Development

As PBWeight software capabilities were being developed, it was becoming evident that a large portion of the existing OpenVSP source code had to be modified. This scenario is far from ideal due to the inevitable decrease in robustness as existing source code is altered. Thus, a RapidFEM Sketch File Editor was developed using Python and invoked from within OpenVSP as seen in Figure 8.

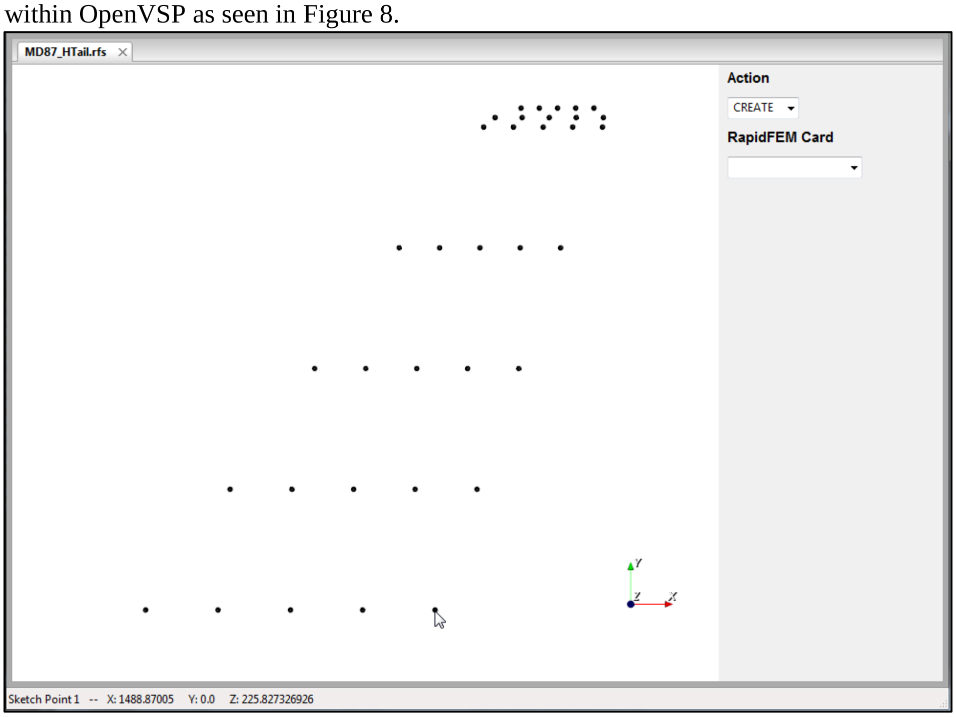


Figure 8: RapidFEM Sketch File Editor.

The RapidFEM Sketch File Editor is a Python-based GUI that use Visualization Toolkit (VTK) as the visualization framework, and wxPython for the GUI itself. As mentioned previously, the RapidFEM Sketch File Editor is called from within OpenVSP to provide a seamless user experience.

The main uses for the RapidFEM Sketch File Editor include the creation of RapidFEM Sketch Files by means of a quick and intuitive GUI, as well as the generation of a comprehensive final FEM that will be used to produce the final weight statement. When the RapidFEM Sketch File export operation is performed in OpenVSP, the RapidFEM Sketch File Editor is automatically opened without any additional user interaction. Upon opening, the RapidFEM Sketch File is automatically loaded into the editor as previously shown in Figure 8.

Once the Sketch Points have been loaded in the RapidFEM Sketch File Editor, the user can then begin assigning RapidFEM attributes to the Sketch Points. For example, to create a SKIN4 card, 'SKIN4' is first selected from the RapidFEM Card combo box. The user then has to click on a series of Sketch Points as well as assign certain parameters associated with the RapidFEM Sketch Card that was chosen.

As points are selected, temporary gray line segments appear denoting where the skin will be placed as shown in Figure 9.

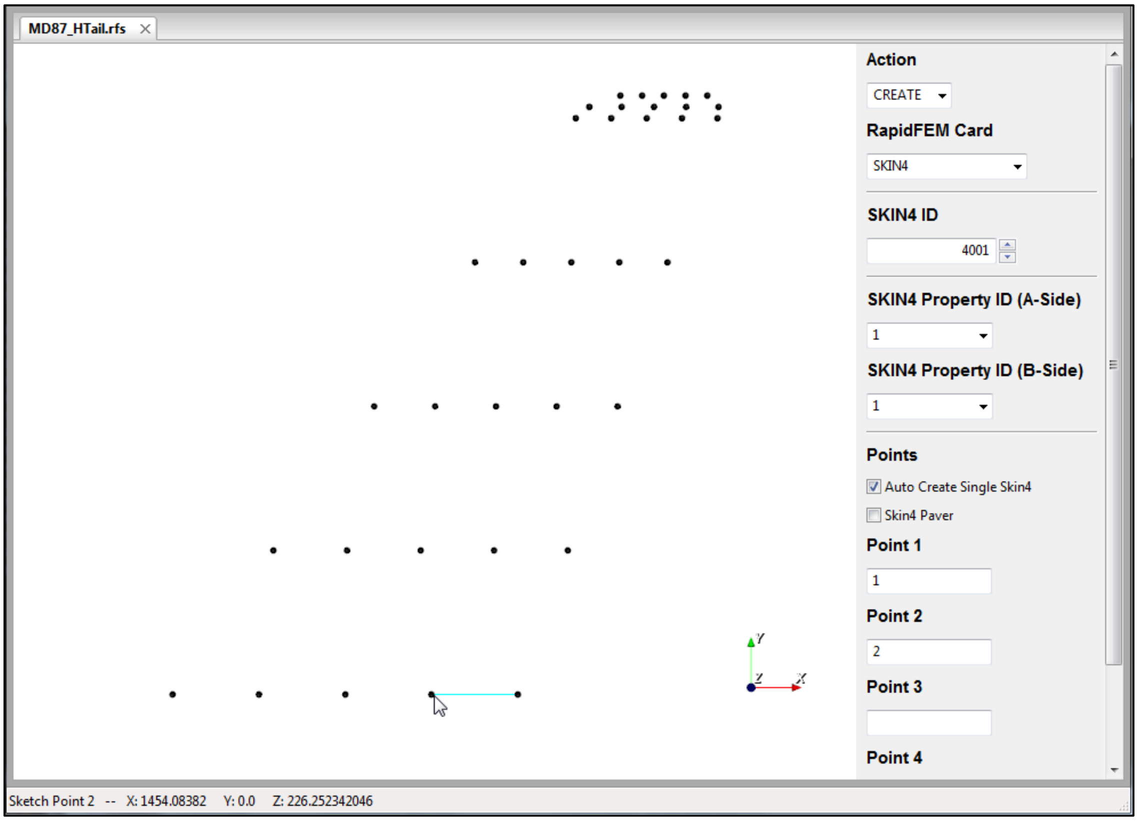


Figure 9: Second Sketch Point Selected.

To create a SKIN4, four Sketch Points have to be selected. Upon the final Sketch Point selection, the Sketch Point Layout Creator Tool automatically connects the fourth Sketch Point to the first Sketch Point that was selected. When a SKIN4 has been placed, all four lines change from gray to blue as seen in Figure 10.

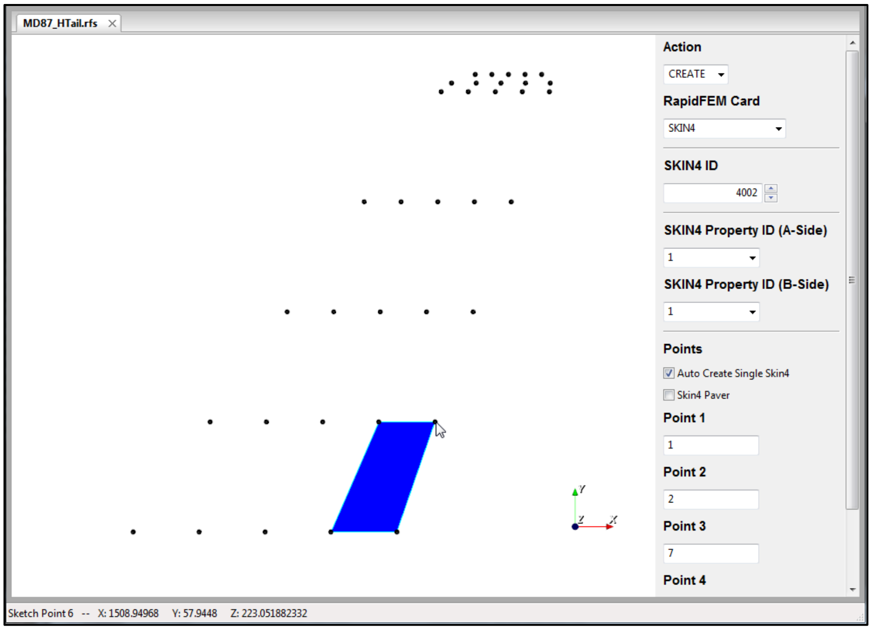


Figure 10: SKIN4 Complete.

When a component has many skin panels, it can be very time consuming and tedious to place skins one-by-one. To expedite the skin creation process, a SKIN4 Paver Tool was created. By using the SKIN4 paver tool, a user is able to create a set of SKIN4s with the same property definitions by selecting four bounding points that define a structured grid of Sketch Points as seen in Figure 11 below.

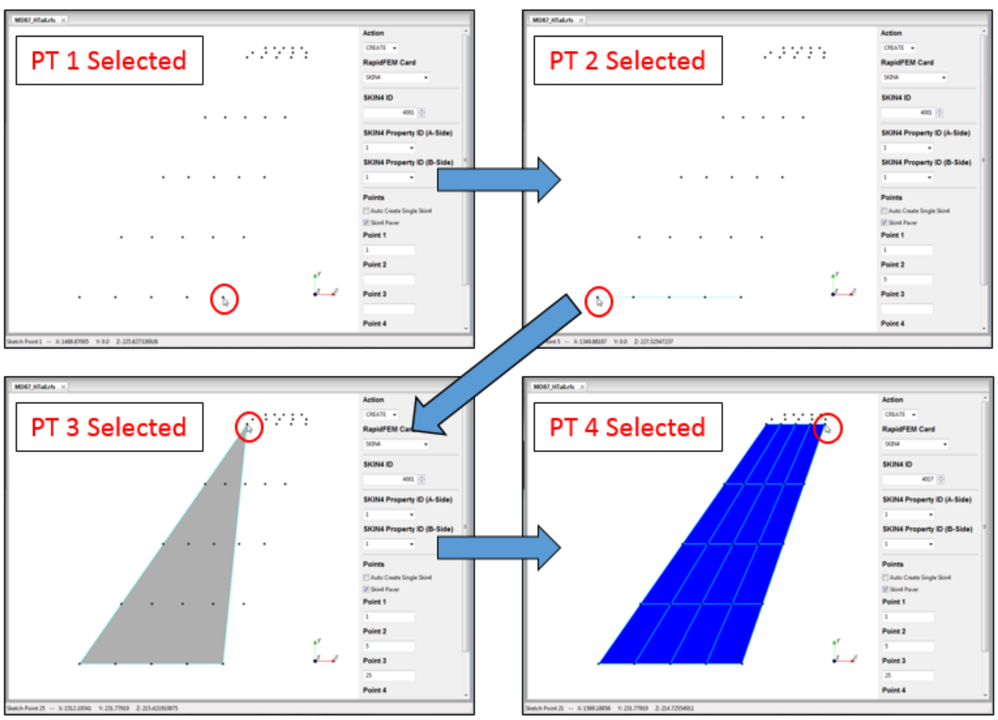


Figure 11: SKIN4 Paver.

The process to assign RapidFEM attributes is common among the other structural RapidFEM attributes such as SKIN3 and BEAM. For example, to add a BEAM to the current RapidFEM Sketch File Editor session, the user simply selects BEAM from the RapidFEM Card combo box. Once BEAM is selected, the rest of the process continues similarly to the process for assigning a SKIN4. The user selects the first Sketch Point they wish to assign a BEAM attribute to as shown in Figure 12.

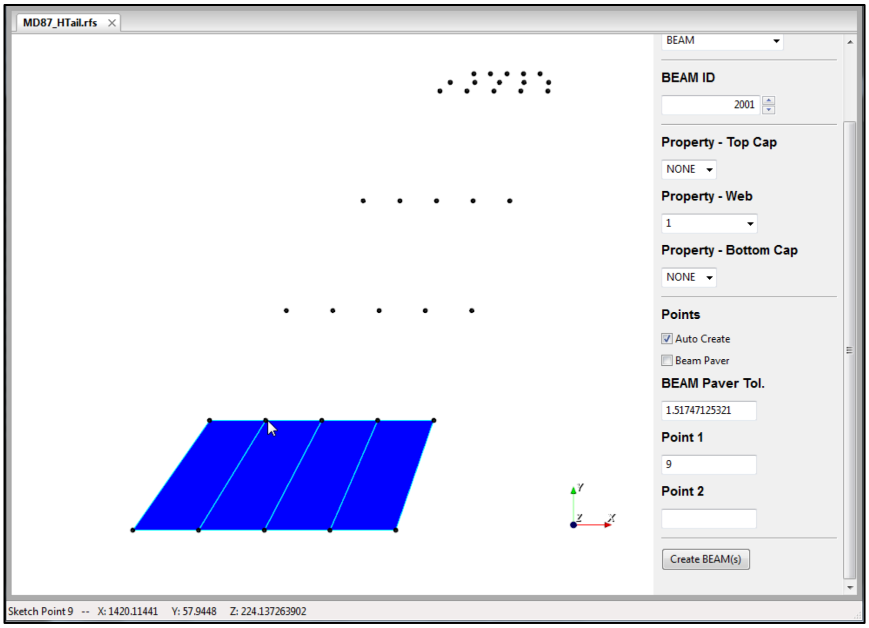


Figure 12: First Sketch Point Selected for BEAM Attribute Assignment.

Because a BEAM is made up of two Sketch Points, the user then has to select a second and final Sketch Point as seen in Figure 13. For BEAMs, the RapidFEM attribute lines turn red. If a SKIN3 was to be created, the attribute lines will turn green.

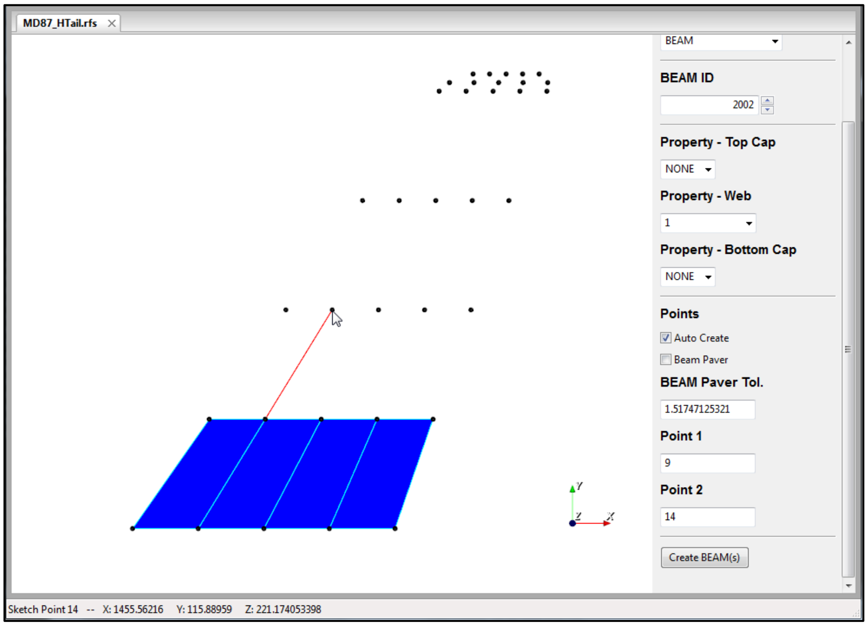
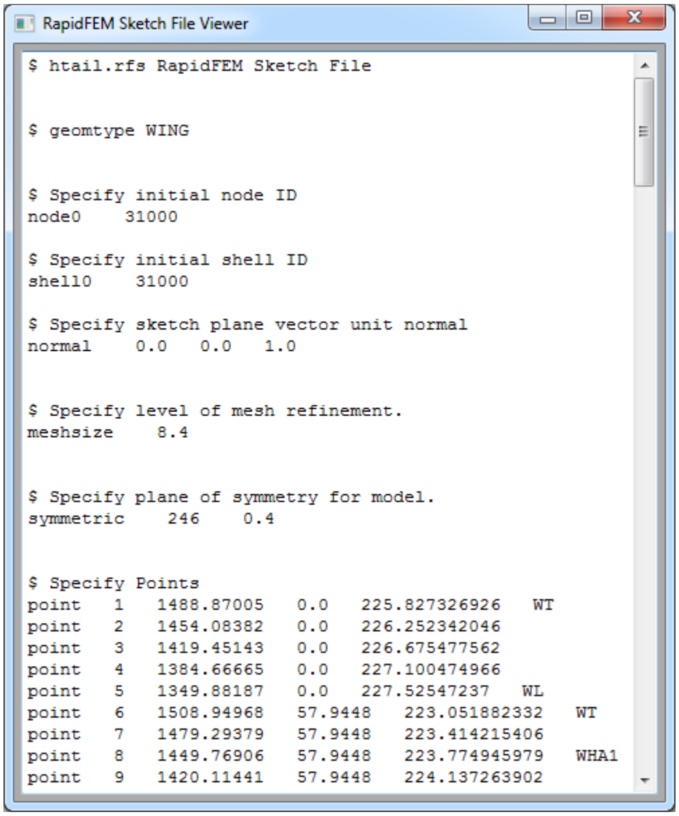


Figure 13: RapidFEM BEAM Attribute Assignment Complete.

As these attributes are being assigned, a Sketch Point Layout data structure is being populated and maintained, which then gets exported in the form of a RapidFEM Sketch file once the Sketch Point Layout is complete as seen in Figure 14.



```
$ htail.rfs RapidFEM Sketch File


$ geomtype WING


$ Specify initial node ID
node0     31000

$ Specify initial shell ID
shell0     31000

$ Specify sketch plane vector unit normal
normal     0.0    0.0    1.0


$ Specify level of mesh refinement.
meshsize     8.4


$ Specify plane of symmetry for model.
symmetric     246     0.4


$ Specify Points
point    1    1488.87005    0.0    225.827326926    WT
point    2    1454.08382    0.0    226.252342046
point    3    1419.45143    0.0    226.675477562
point    4    1384.66665    0.0    227.100474966
point    5    1349.88187    0.0    227.52547237    WL
point    6    1508.94968    57.9448    223.051882332    WT
point    7    1479.29379    57.9448    223.414215406
point    8    1449.76906    57.9448    223.774945979    WHA1
point    9    1420.11441    57.9448    224.137263902
```

Figure 14: RapidFEM Sketch File View.

Similar to how MSC Patran operates, there are four different action types when working with RapidFEM explicit sketch cards that include ‘create’, ‘modify’, ‘show’, and ‘delete’. The ‘show’ action allows the user to easily observe a particular RapidFEM entity, as well as distinguish it from the rest of the currently assigned attributes as seen in Figure 15, which demonstrates a ‘show’ action for SKIN4 with ID of 4003. When a RapidFEM attribute entity is selected to be shown, such as a SKIN4, the lines representing that entity are highlighted.

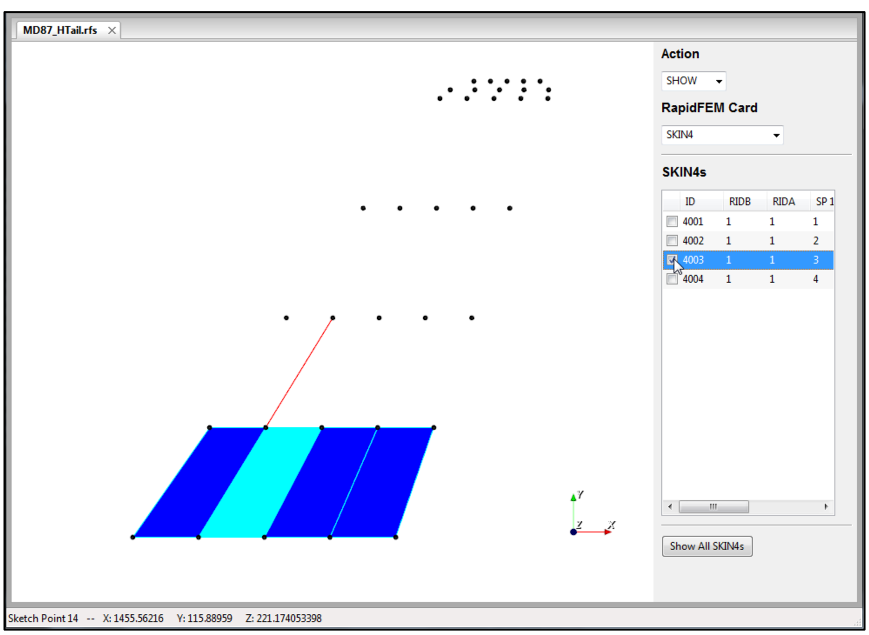


Figure 15: Show SKIN4 with ID 4003.

IV. Demonstration of the PBWeight Tool on the MD-87 Configuration

As previously described in section II, the first step in the process shown in Figure 1 was to develop parametric geometry representations that resemble each of the configurations. This was accomplished within the Open Vehicle Sketch Pad (OpenVSP) software package, since the accompanying aircraft parameterization style serves as an excellent basis for conceptual-level design and analysis.

A. Creating MD-87 Model Using OpenVSP

During the literature review, a three-view schematic of the MD-87 was obtained from (Ref. 4), as shown in Figure 16.

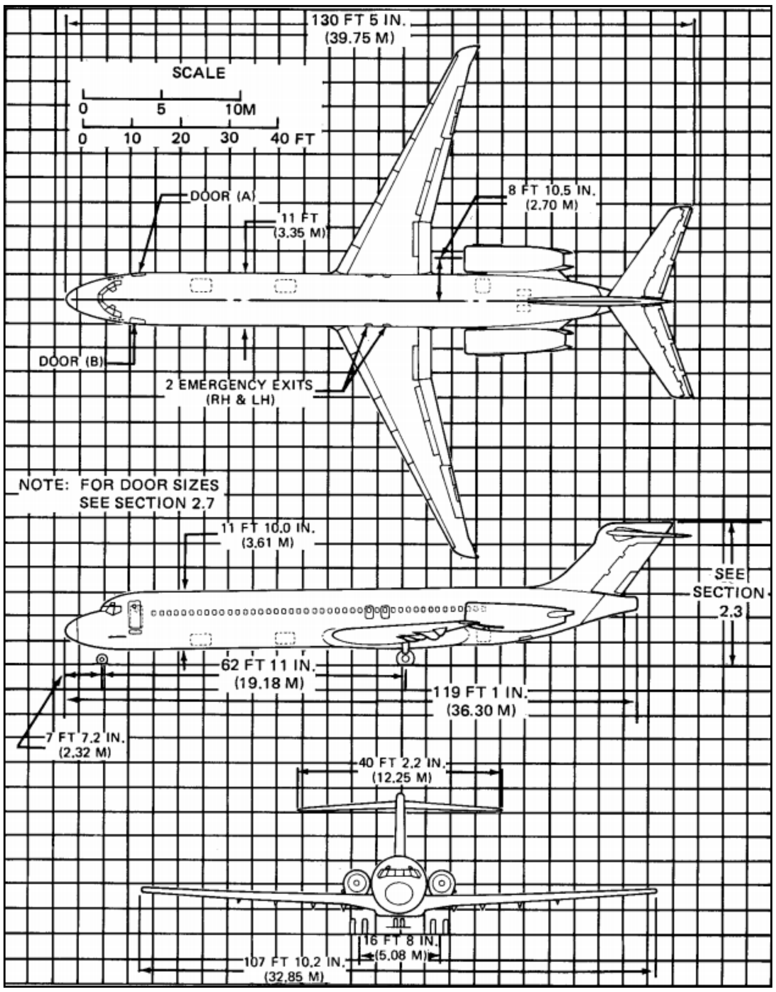


Figure 16: Three-view Schematic of the MD-87 (Ref. 4).

The model was rapidly built within OpenVSP by placing the schematics in the background, fixing component dimensions to published specifications, scaling the components to match the dimensions of the schematic, and shaping the components as necessary. Following this procedure, each model was built within approximately one day of work. Figure 17 through Figure 19 display the overlay comparison between the two OpenVSP models and their corresponding schematics.

Regarding the MD-87 OpenVSP model, the fuselage, undercarriage, and nacelle were modeled using the Fuselage component; the wing, horizontal/vertical tail, and pylon were modeled using the Wing component. Although the undercarriage, nacelles, and pylon were modeled within OpenVSP, these components were not included in the final FEM or the optimization results to provide a consistent model for comparison with the Phase I results.

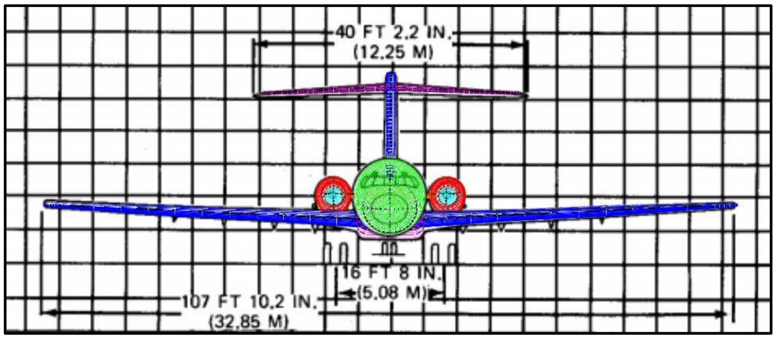


Figure 17: MD-87 Front View.

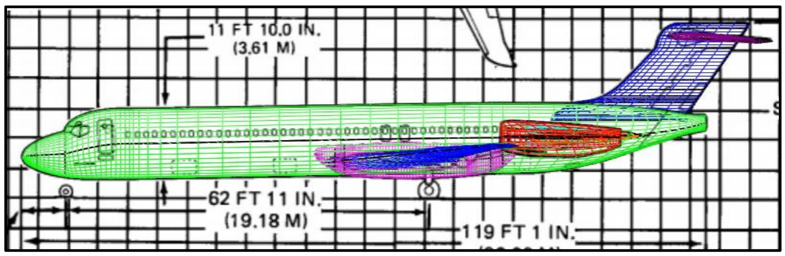


Figure 18: MD-87 Side View.

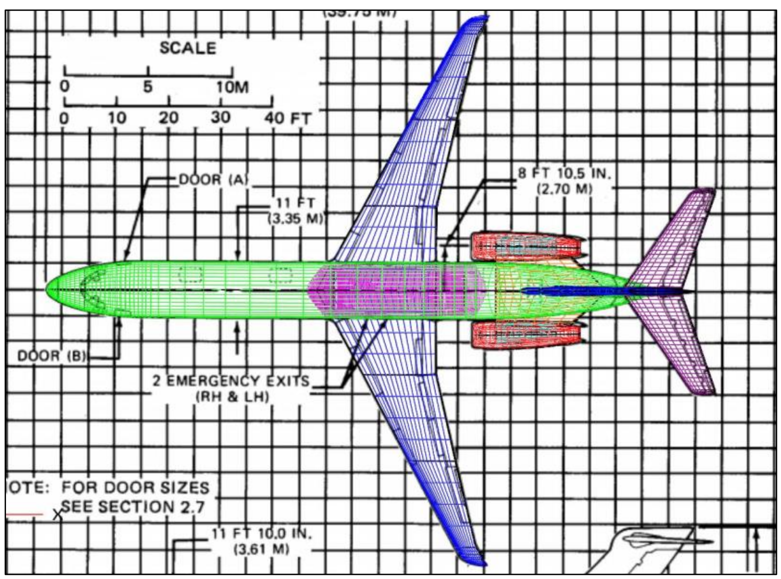


Figure 19: MD-87 Top View.

B. RapidFEM Sketch File Development

Sketch files were created for the various MD-87 aircraft components. Illustrations of the sketch files can be seen in Figure 20. All components have their respective sketch files. Additionally, the time spent to build each sketch file, both by hand and by using the PBWeight software, is detailed in Table 1. It can be seen that an average speed up of 7x for the MD-87 aircraft components is made possible with the PBWeight software. This serves as a point of reference to show the dramatic improvement in time spent laying out sketch points for a given geometry compared to the Phase I effort.

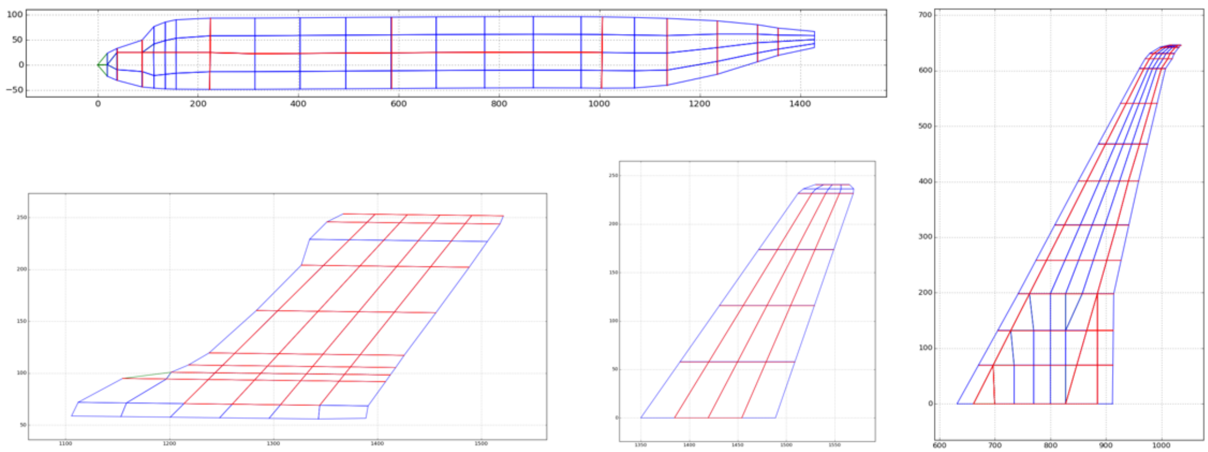


Figure 20: Visualization of MD-87 Component Sketch Files.

Table 1: Manual Time vs. PBWeight Time Spent Building MD-87 Component Sketch Files.

Component	Manual Time [hr]	PBWeight Time [hr]
Fuselage	4.0	0.5
Wing	3.0	0.5
Vertical Tail	2.0	0.25
Horizontal Tail	1.5	0.25

C. FEM Generation and Merging

The FEM (Figure 21) corresponding to the fuselage sketch file has nine bulkheads being modeled (from end to end). The passenger floor is located at the 50% height location and continues at a constant height for the cockpit floor. The FEM corresponding to the wing sketch file is shown in Figure 22. There are two primary spars being modeled within the wing. The first (from LE to TE) is the forward spar, acting as the boundary between the wing slats and the wing box. Next is the aft spar, acting as the boundary between the wing box and the various wing trailing edge control surfaces. The FEMs corresponding to the vertical tail and horizontal sketch files are displayed in Figure 23 and Figure 24, respectively.

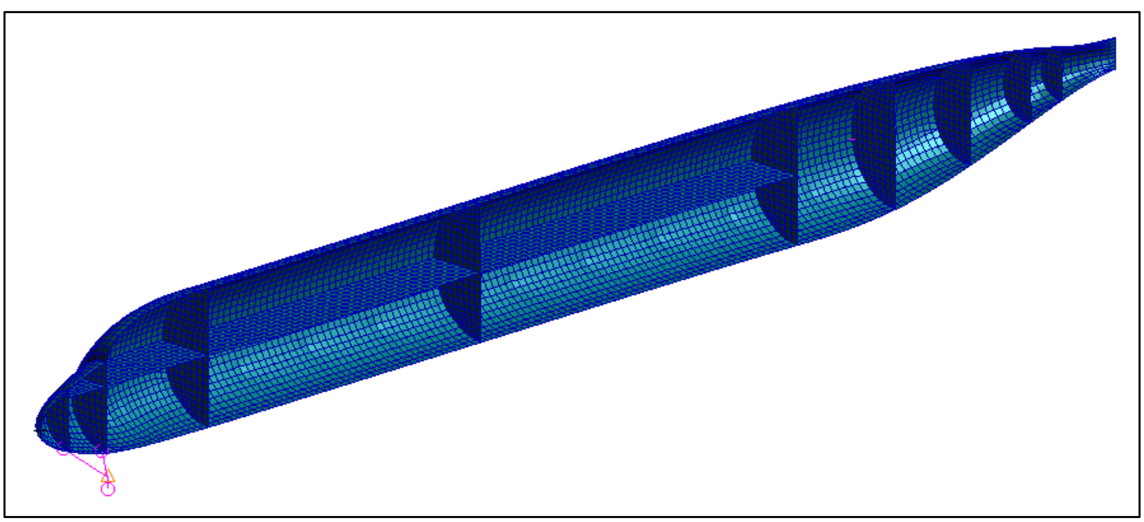


Figure 21: MD-87 Fuselage FEM Creation with Internal Structure.

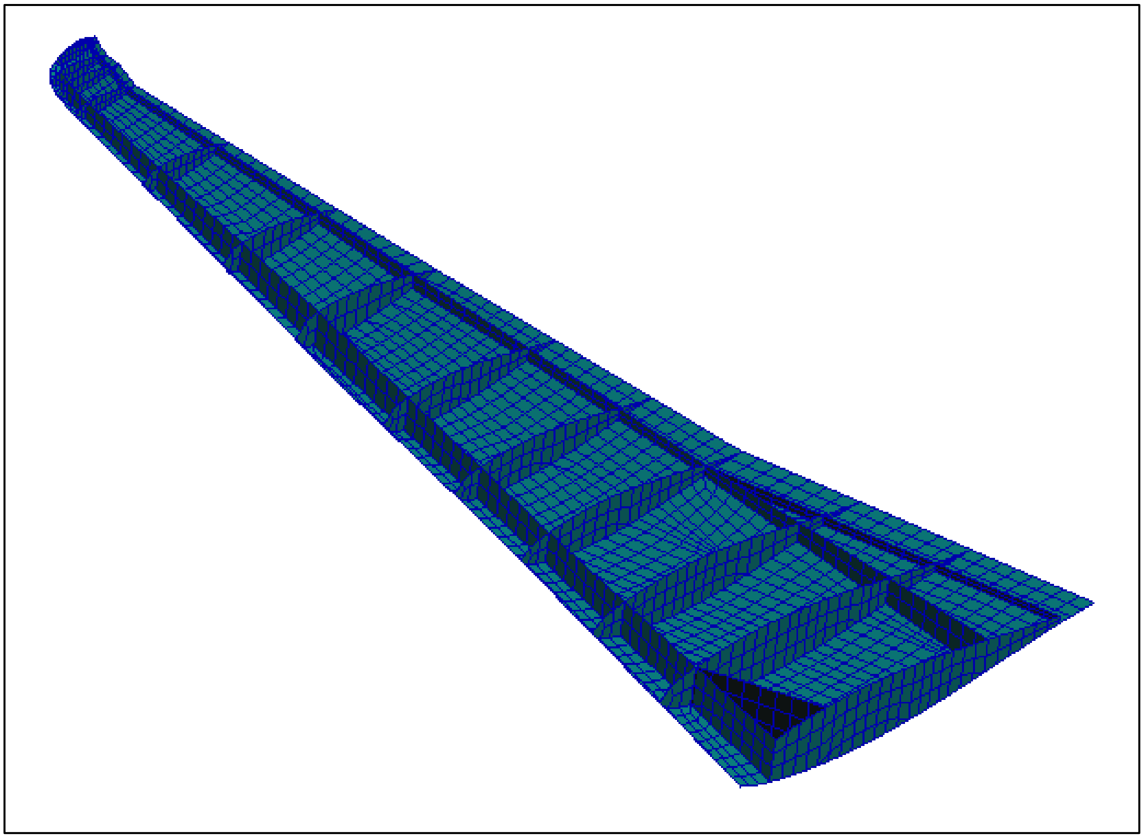


Figure 22: MD-87 Wing FEM with Internal Structure.

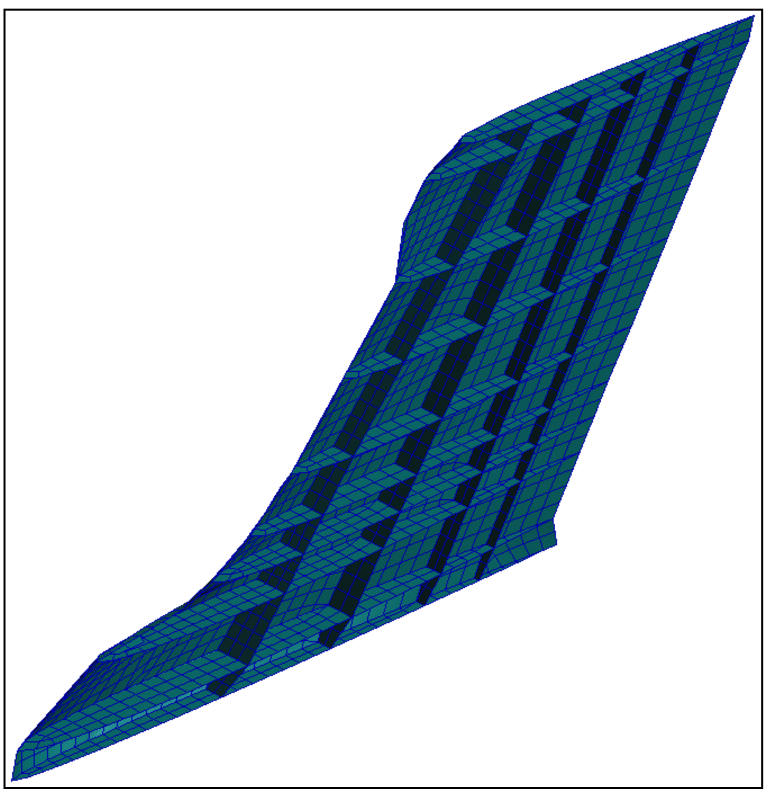


Figure 23: MD-87 Vertical Tail FEM with Internal Structure.

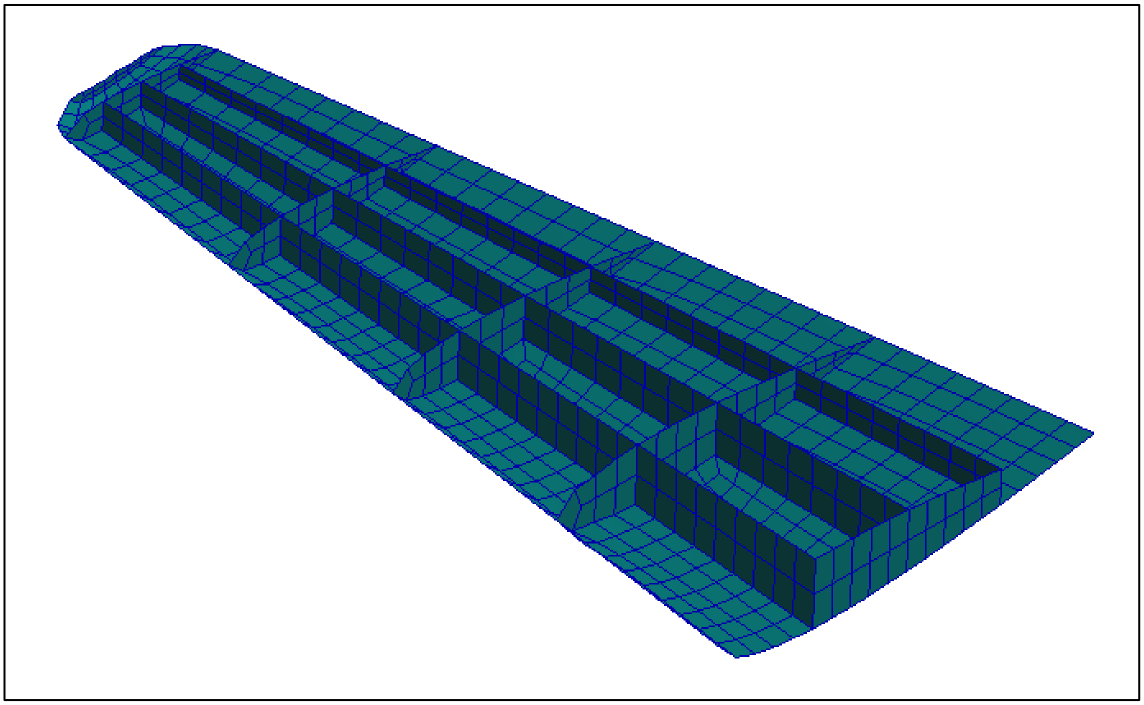


Figure 24: MD-87 Horizontal Tail FEM with Internal Structure.

Currently, FEM property regions are unique to each sketch file object (necessary for specifying the non-structural mass (NSM) and thicknesses in each structure), thereby relieving the user from a priori region definitions and providing greater ease in the manipulation of merge/trim regions. Furthermore, the ability to manipulate merge/trim regions to the level of refinement present in the sketch file helps reduce the runtime by preventing non-essential regions from being implicitly included in the merge/trim process because it is marked under the same property as other sketch point objects essential to the merge/trim process as shown in Figure 25.

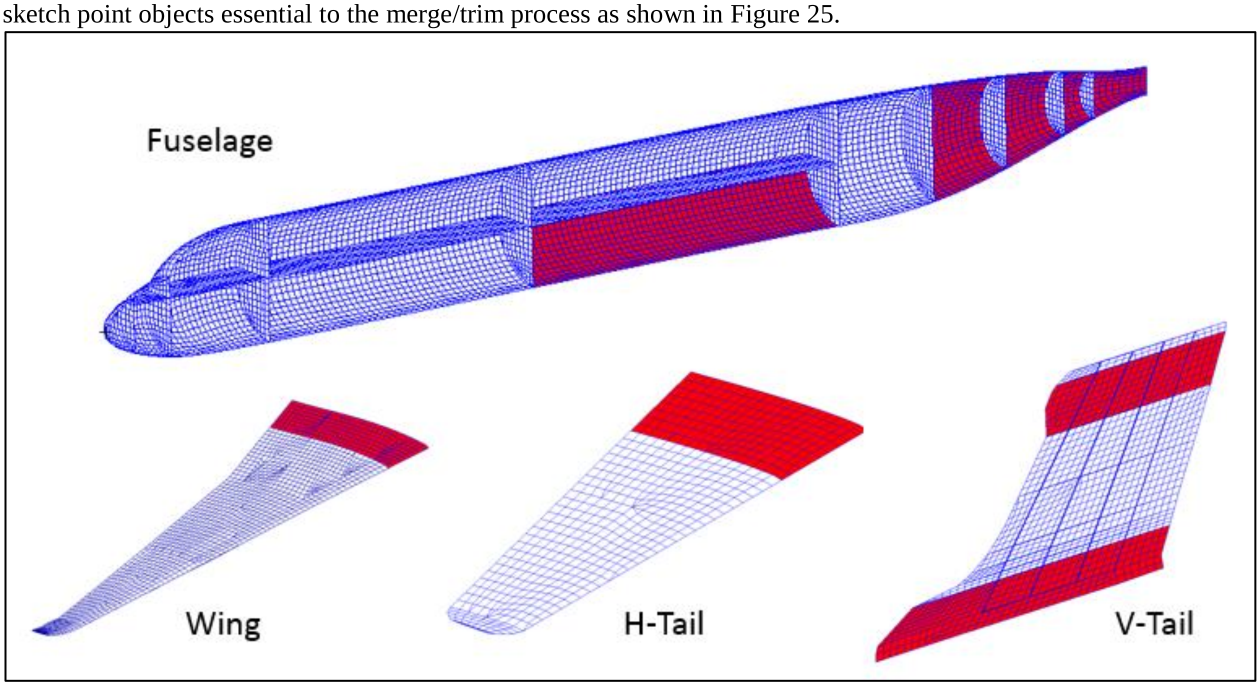


Figure 25: MD-87 Merging Property Regions.

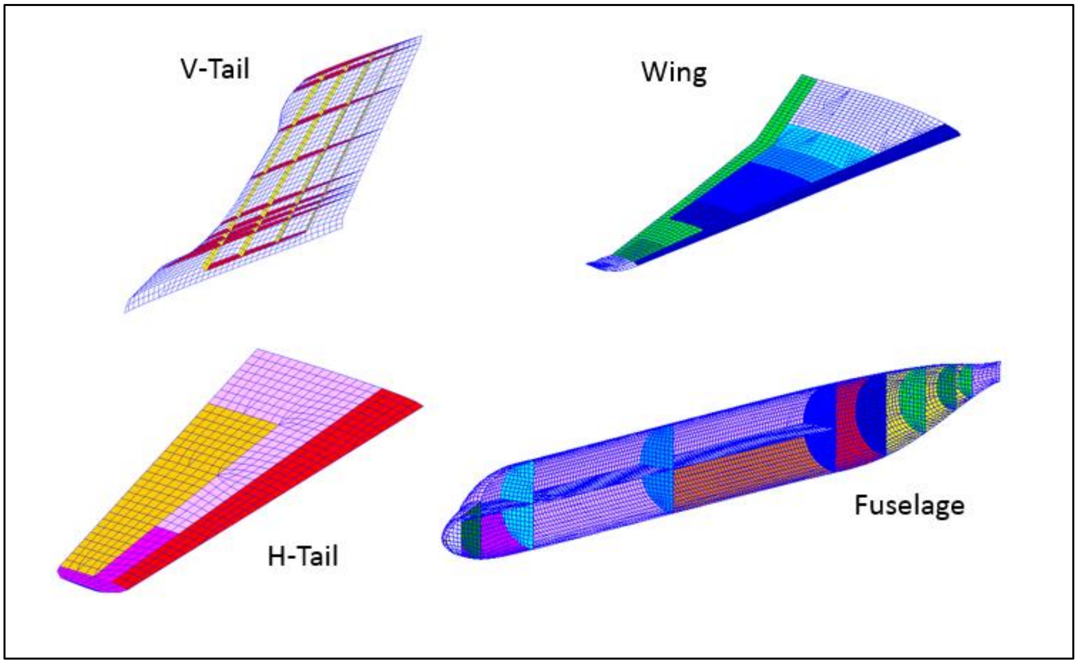


Figure 26: MD-87 Structural Component Property Region Layout.

To accurately model the NSM distribution in each property region, the area of each property region must first be determined. The fixed mass in each property region is then divided by the area of each property region to give the NSM in mass per unit area format. Table 2 provides a list of fixed mass contributions and corresponding weights and locations (Ref. 1). The 'Type' column shows a list of the corresponding RapidFEM cards used to model each of the fixed masses.

Table 2: MD-87 Fixed Mass Contributions to Fuselage & Wing (in Pounds).

Aircraft Component	MD-80	Type	Location
Nacelle	5340	ATTACHMENT	Fuselage
Nose gear	550	LDGR	Fuselage
Main gear	4790	LDGR	Wing
Engine	8820	ATTACHMENT	Fuselage
Nozzle system and $T_{reverser}$	1540	ATTACHMENT	Fuselage
Fuel system	640	NSM	Fuselage
Avionics and instruments	2130	NSM	Fuselage
Surface controls	2540	NSM	Wing/Emp
Hydraulic system	540	NSM	Fuse/Wing
Pneumatic system	1720	NSM	Fuse/Wing
Auxiliary power units (APU)	840	NSM	Fuselage
Oxygen system	220	NSM	Fuselage
Environmental control system (ECS)	1580	NSM	Fuselage
Anti-icing system	550	NSM	Wing
Furnishings	8450	NSM	Fuselage
Miscellaneous	3650	NSM	Fuselage
Fuel	14422	TANK	Wing
Payload (lb)	16103	NSM	Fuselage

When combining the fuselage and the wing, two regions were trimmed. The first was the leading and trailing sections of the wing inside the fuselage, as seen in Figure 27, as well as the fuselage carry-through inside the wing, as seen in Figure 28. Note that various elements have been removed from the images in order to provide a better view of the merge/trim result. Next, the resulting FEM was combined with the vertical tail, of which any portion inside the fuselage was trimmed, as seen in Figure 29. That was combined with the horizontal tail, of which any portion inside the vertical tail was trimmed, as seen in Figure 30.

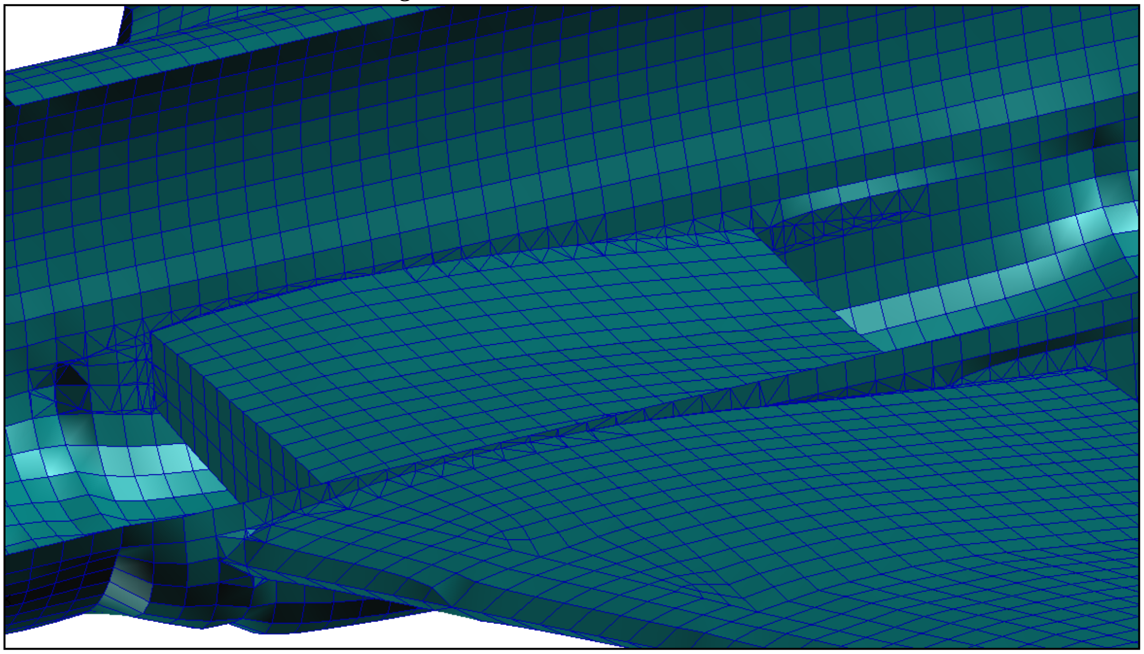


Figure 27: MD-87 LE/TE Wing Box in Fuselage Trim.

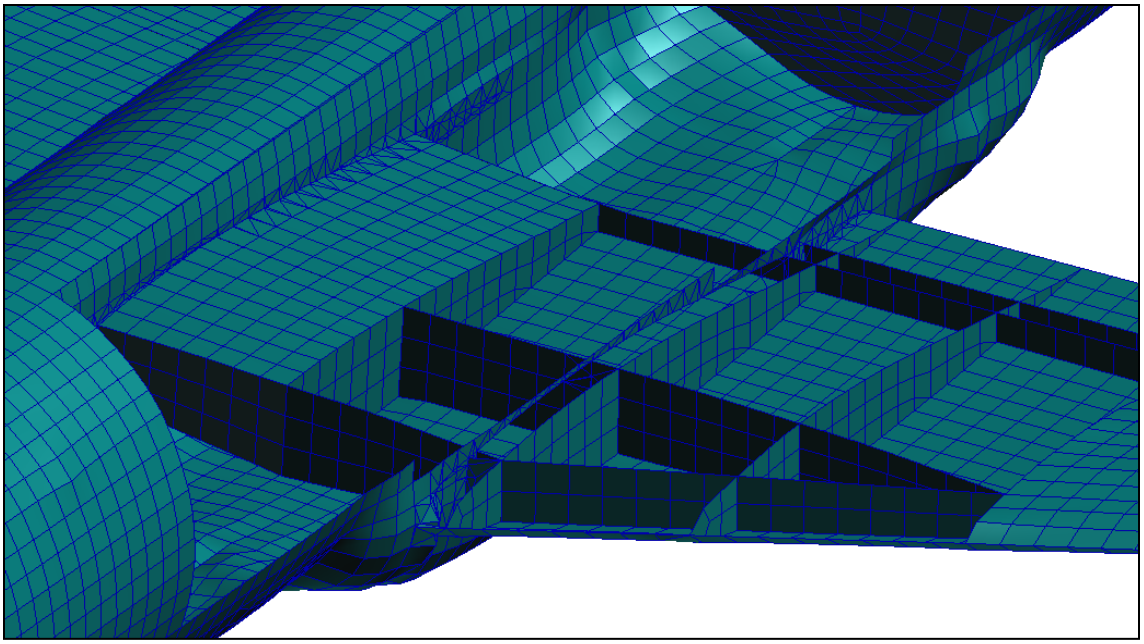


Figure 28: MD-87 Fuselage in Wing Carry-through Trim.

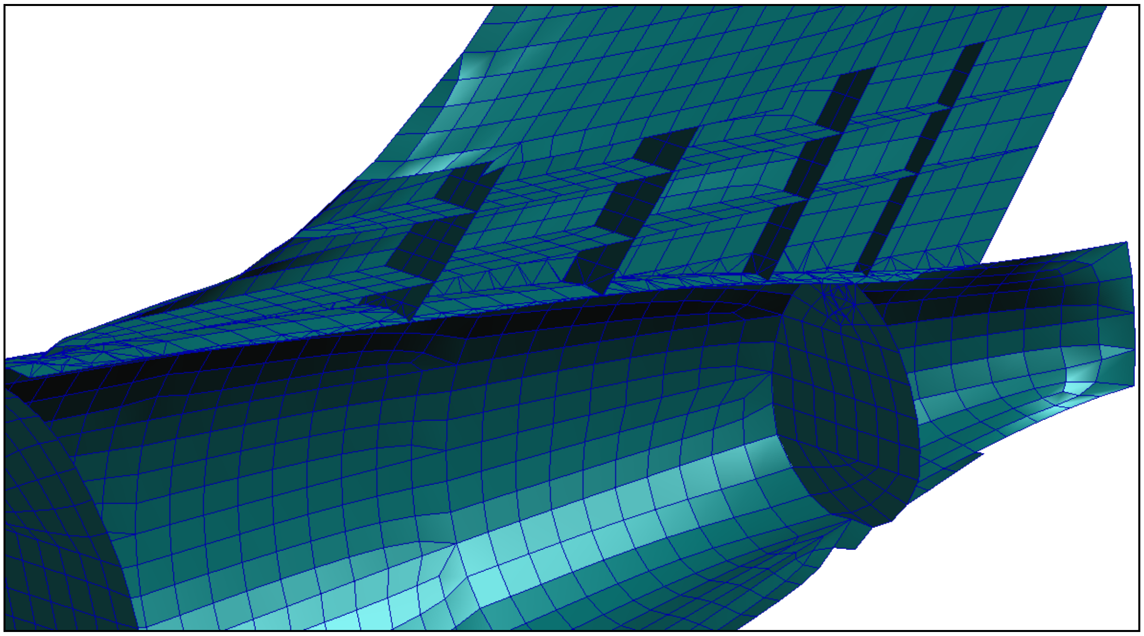


Figure 29: MD-87 Vertical Tail in Fuselage Carry-through Trim.

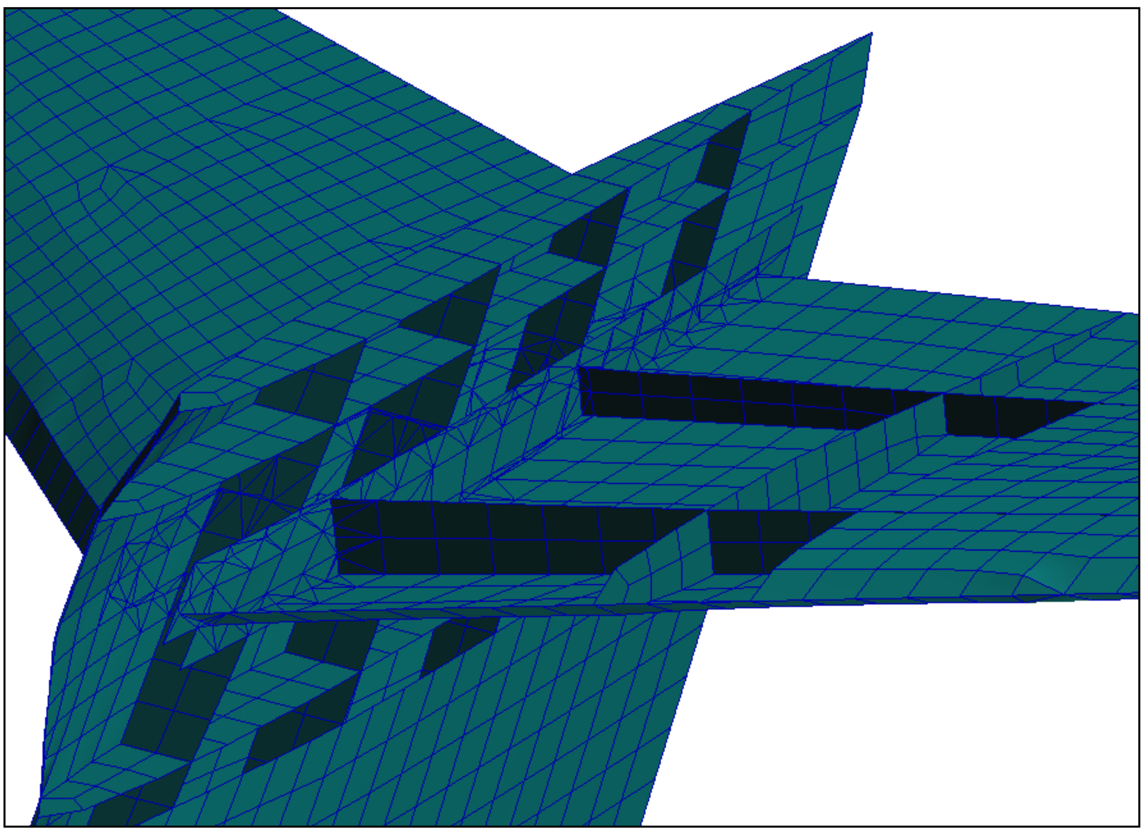


Figure 30: MD-87 Horizontal Tail in Vertical Tail Carry-through Trim.

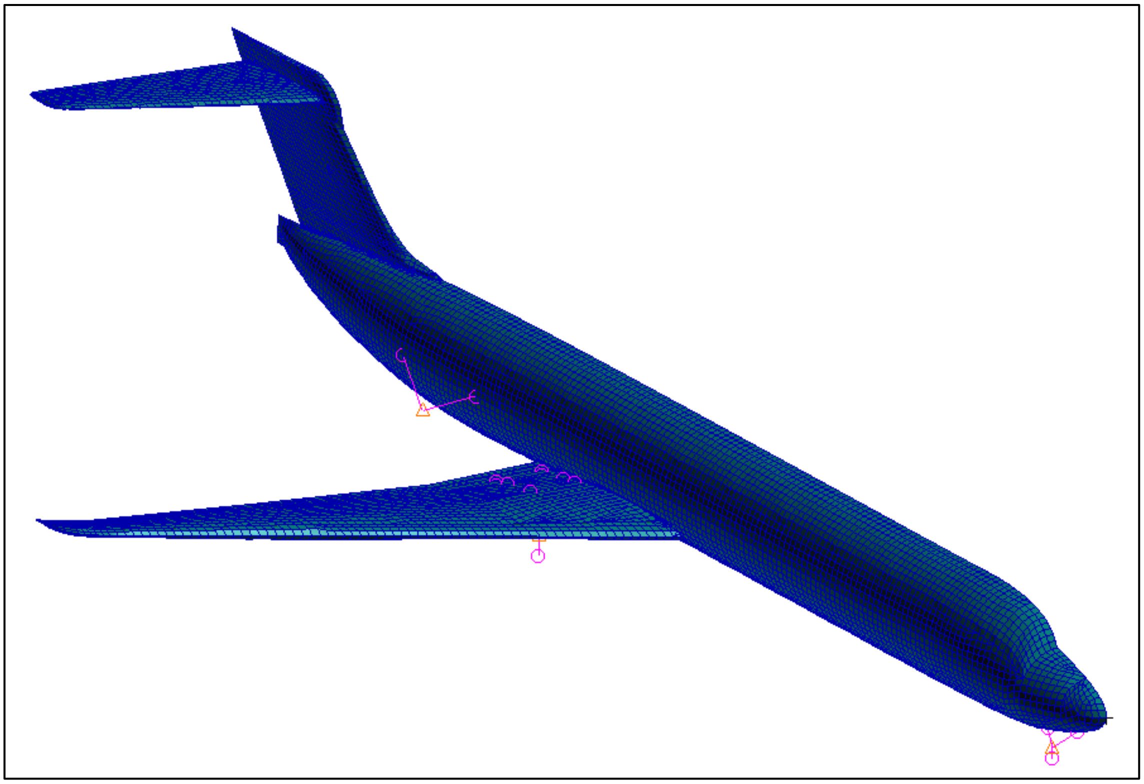


Figure 31: MD-87 Merged/Trimmed Half Model FEM.

It should be noted that the figures above showing the merged/trimmed FEM sections are of a full model in order to fully demonstrate PBWeight's full model capabilities. Because the two chosen load cases discussed later in this paper are symmetric load cases, the final optimization was performed on a half model in order to speed up the time required to arrive upon optimization results.

The merge/trim process described above is initiated from the RapidFEM Sketch File Editor. Once the individual component FEMs are generated by RapidFEM, the user selects a joint file, which specifies the property regions being merged and trimmed for each component, and RapidFEM is executed to generate a merged FEM of two different components. This process is repeated for each component until a final comprehensive merged FEM is created.

V. Example Applications

A. MD-87: Example Problem Description

The goal for the analysis effort was to estimate the weight of the primary structural components of a commercial transport similar to an MD-87 aircraft. The problem statement for the analysis included assuming a uniform metallic structure (aluminum), fixed non-structural mass, two separate load cases as specified in the FAA Regulations (FAR) Part 25, and defined stress constraints or allowable stresses.

The material used for the MD-87 structure was aluminum alloy 7068, with an ultimate tensile strength (F_{tu}) around 103 kilo-pounds per square inch (ksi) (Ref. 5). Two load cases were considered to size the fuselage and wing structural components, as defined by FAR Part 25 (Ref. 6). These load cases include the 2.5g pull-up maneuver and the abrupt pitch maneuver. Table 3 provides the flight conditions for each of the two load cases. The flight conditions include high subsonic speed coupled with high dynamic pressure. In the analysis, all components were sized to 34.3ksi stress allowable. It is important to note that the effects of turbulent gust loads, fuselage stiffeners, rings, frames, and flutter constraints were implicitly considered within the allowables.

Table 3: MD-87 Load Case Flight Conditions.

Load Case	Mach Number	Altitude [ft]
2.5g Pull-Up	0.84	Sea Level
Abrupt Pitch	0.84	Sea Level

B. MD-87: Baseline Optimization Results

The baseline optimization analysis was carried out on the MD-87 half-model for the 2.5g Pull-Up case seen above in Table 3. The process for optimizing the MD-87 half model was unchanged from the Phase I (Ref. 3) effort and consisted of using Nastran's Solution 200 optimizer in conjunction with static aeroelastic analysis (Nastran Solution 144) for the load case. The design variables consisted of the property region thickness over the entire FEM model, with the initial thicknesses defined in the RapidFEM 'PROP' cards. The thicknesses were constrained by a minimum gage of 0.125 inches for the fuselage and 0.1 inches for the other components, while the stresses were constrained by the allowable mentioned above. The baseline results achieved during the Phase II effort were very similar to the results achieved in Phase I (Ref. 3).

VI. Conclusions

The purpose of this effort was to create an efficient and user-friendly interface for streamlining the internal structural layout process, assigning material properties, attachments, loads, and optimization analysis information. The tools and methods developed within the PBWeight software and described in this paper demonstrate a significant reduction in the time, as compared to the Phase I effort (Ref. 3), required to produce meaningful physics-based weight statements with excellent accuracy at the conceptual design level. Evidence has been presented that conveys an average of 7x speed up for RapidFEM Sketch File creation process.

Future development efforts will be focused on further increasing the overall robustness of the PBWeight software as well as incorporating even more automated tools. These automated tools include automated wing and fuselage layout tools capable of producing complete wing or fuselage RapidFEM Sketch Files that when processed by RapidFEM, will produce complete FEMs requiring minimal user input. Another valuable capability M4 Engineering plans on developing for the PBWeight software is a surrogate modeling capability. A user will be able to construct a baseline model using the existing PBWeight toolset, then using the future PBWeight surrogate modeling capability, effortlessly run parametric geometry/structural trade studies on a countless number of design parameters (i.e. most or all of the available design parameters for each supported OpenVSP component). Some design parameters include, wing sweep, wing span, fuselage length, fuselage width, etc.

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References

[1]Nicolai, L.M., and Carichner, G.E. *Fundamentals of Aircraft and Airship Design: Volume 1 - Aircraft Design*, American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2010.

[2]Raymer, D. P. *Aircraft Design: A Conceptual Approach*, American Institute of Aeronautics and Astronautics, Inc., 2012.

[3]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.

[4]Airport Compatibility Group, *MD-80 Series: Airplane Characteristics for Airport Planning*, Long Beach, CA : Douglas Aircraft Company, 1990.

[5]Federal Aviation Administration (FAA), *Metallic Materials Properties Development and Standardization (MMPDS)*, [Document] s.l. : Federal Aviation Administration (FAA), 2012.

[6]U.S. Government Publishing Office (GPO), TITLE 14 - Aeronautics and Space, *Electronic Code of Federal Regulations*, [Online] U.S. Government Publishing Office (GPO), December 16, 2014. http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title14/14cfr25_main_02.tpl,

[7]Ordaz, I., Geiselhart, K. A., and Fenbert, J. W. "Conceptual Design of Low-Boom Aircraft with Flight Trim Requirement," *32nd AIAA Applied Aerodynamics Conference*, AIAA, Atlanta, GA, 2014.
[8] Aircraft Familiarization DC-9, MD-80, MD-90, [Online]
[9]Boeing, How the Environmental Control System Works on Boeing Airplanes, *Boeing*, [Online] http://www.boeing.com/boeing/commercial/cabinair/environmentcontrol.page,
[10]Federal Aviation Administration, Hydraulic and Pneumatic Power Systems, *Federal Aviation Administration*, [Online] http://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/amt_airframe_handbook/media/ama_ch12.pdf,
[11]PBS, Anatomy of a Jetliner, *NOVA*, [Online] PBS, February 2004. http://www.pbs.org/wgbh/nova/aircrash/jetl-nf.html. ,
[12](FAA), Federal Aviation Administration, *Metallic Materials Properties Development and Standardization (MMPDS)*, s.l. : Federal Aviation Administration (FAA), 2012.
[13]M4 Engineering, Inc. *RapidFEM User Manual Version 5.0*, Long Beach, CA : s.n., May 2015.