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Enabling Rapid and Robust Structural Analysis During Conceptual Design

Lloyd B. Eldred, Sharon L. Padula, and Wu Li
Langley Research Center, Hampton, Virginia

February 2015

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Langley Research Center, Hampton, Virginia

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Space Administration

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Abstract

This paper describes a multi-year effort to add a structural analysis subprocess to a supersonic aircraft conceptual design process. The desired capabilities include parametric geometry, automatic finite element mesh generation, static and aeroelastic analysis, and structural sizing. The paper discusses implementation details of the new subprocess, captures lessons learned, and suggests future improvements. The subprocess quickly compares concepts and robustly handles large changes in wing or fuselage geometry. The subprocess can rank concepts with regard to their structural feasibility and can identify promising regions of the design space. The automated structural analysis subprocess is deemed robust and rapid enough to be included in multidisciplinary conceptual design and optimization studies.

Nomenclature

API	=	application programming interface
BDF	=	bulk data file
CFD	=	computational fluid dynamics
CG	=	center of gravity
DOE	=	design of experiments
GUI	=	graphical user interface
FEA	=	finite-element analysis
FEM	=	finite-element model
MOS	=	margin of safety
NSM	=	non-structural mass
OML	=	outer mold line of aircraft
VSP	=	Vehicle Sketch Pad

1 Introduction

Conceptual design of a low-boom supersonic vehicle is difficult due to the large number of competing objectives and constraints to be considered. For example, a supersonic transport aircraft must operate safely and efficiently at subsonic, transonic, and supersonic speeds. It must be able to deliver a reasonable amount of payload over a long range without creating a noisy environment inside or outside the vehicle. The cost of the vehicle and its maintenance and operation must be small enough to allow the owner to make a profit. Thus, a large number of disciplinary analyses such as aerodynamic performance, propulsion, sonic boom prediction, and flight dynamics are required to evaluate the competing objectives.

The NASA Fundamental Aerodynamics Program has developed an integrated process for conceptual design of low-boom supersonic aircraft (refs. [1] - [3]). This process is implemented in the ModelCenter® framework (ref. [4]), which is a product of Phoenix Integration. The integrated process enables a conceptual designer to evaluate a new concept using consistent geometry and mission parameters across a range of disciplinary analyses. A rapid and robust structural analysis subprocess is a recent addition to the integrated process.

Structural analysis is rarely included in the conceptual design process because neither the finite element model (FEM) nor the aeroelastic load cases are constructed prior to preliminary design. Enabling structural analysis during an earlier design phase reduces analysis uncertainty and improves the quality of concepts in the down-selected set. For example, better estimates of the vehicle weight and volume are needed to determine how much fuel and payload can be carried. Details of the structural weight distribution are needed to confirm the location of the center of gravity (CG) under all flight conditions. Improved estimates of the vehicle CG and trim parameters influence the low-boom shaping. The choice of structural materials and layout impact both the aeroelastic characteristics and the cost. Finally, concept designers need to consider how changes in the outer mold line (OML) change the internal structure.

Structural analysis can be performed during conceptual design if the appropriate input files (e.g., FEM and load sets) can be constructed automatically for each new OML considered by designers. The current approach constructs a conceptual level finite element model of the aircraft fuselage and wing, generates a very small set of critical load cases, sizes the structure to support those loads, and computes the structural weight from that sizing. This approach has been shown to be both rapid and extremely robust and is well suited for comparing designs across a large design space.

The rapid structural analysis subprocess was applied to a large number of supersonic concepts. The concepts were developed for different missions, and thus vary in size, but all have similar supersonic cruise Mach number and high cruise altitude. A typical low-boom flight demonstrator (LBFD) concept is shown in figure 1 (ref. [5]). The baseline design has a single embedded engine, a fuselage length of 108 ft, a target cruise weight of 21,000 lb, a cruise Mach number of 1.6, and a cruise altitude of 50,000 ft. Many candidates for the LBFD mission were evaluated and compared using the rapid structural analysis subprocess.

Figure 1. Embedded engine LBFD concept.

2 Overview of Rapid Structural Design Subprocess

Reference [1] documents the conceptual design process and discusses many advantages to using commercial framework software. One significant advantage is the ability to set up a wide variety of iterative processes and thereby implement parameter studies, design of experiment (DOE) studies, and multidisciplinary optimization tasks. Each cycle of the iterative process automatically changes the geometric variables, repeats analysis modules, links module outputs to subsequent module inputs, and collects the final output values. The ModelCenter framework provides a simple and flexible mechanism for linking the results of one analysis with the inputs to the next analysis. The framework software handles all of the data manipulation and allows the conceptual designer to focus on the design task.

Adding a structural analysis subprocess to the existing conceptual design process is technically challenging. The software modules must incorporate a lot of expert knowledge in order to be successful. The FEM must be as simple as possible and yet must return credible results. The results of the analysis and sizing must reliably rank supersonic concepts from best structure to the worst structure. The total computer processing time must be small, the user inputs must be easy for non-experts in structural analysis to understand, and the numerical methods must be insensitive to large OML changes.

Many different steps are required to add structural analysis to the conceptual design process. These steps include parametric OML geometry, internal structural layout, structural model meshing, load case creation, static analysis, and sizing. Each step operates automatically after some initial tuning by a knowledgeable user. Figure 2 illustrates the steps required to create the FEM for the vehicle. Figure 3 shows the steps involved in structural sizing of the vehicle to produce a design that can support the critical mission loads. Each of these steps will be discussed in section 2 and evaluated in sections 3 and 4.

The simplified finite element model of the aircraft consists of a half-model of the vehicle fuselage and wing. The fuselage is modeled with elliptical cross sections that can vary in diameter and vertical position. The wing is modeled as a spanwise series of trapezoidal sections with allowance for dihedral, twist, and varying thicknesses. Separate tools are available to extract geometry data from the system, to create the structural design, and to generate the mesh itself. This approach works extremely well; it utilizes the expertise within the modeling team, pinpoints modeling errors, and focuses the design intent on the appropriate areas. The software is built in a modular fashion so that the wing generation tools are capable of being called to generate tail and canard surfaces and the fuselage tools could be used in the future to generate nacelles. The current subprocess uses MSC.Nastran® software (ref. [6]), however other structural analysis codes could be included in the future.

2.1 Geometry Extraction

The conceptual design process described in reference 1 includes many options for creating or changing the baseline OML. One option is to import a file that defines each aircraft component as a rectangular surface grid. Alternately, Vehicle Sketch Pad (VSP) has a graphical user interface (GUI) for assembling a new vehicle OML from generic aircraft components (ref. [7]). Finally, Jaguar software can produce high-precision aircraft geometries by interpolating between user-defined key sections (ref. [8]). Both VSP and Jaguar can define and change design variables such as wing section twist and fuselage section width. Both software packages can be executed efficiently in batch mode. The user can input design variable values and run analyses manually or can set up an iterative process that will change design variable values and rerun the analysis for updated OML.

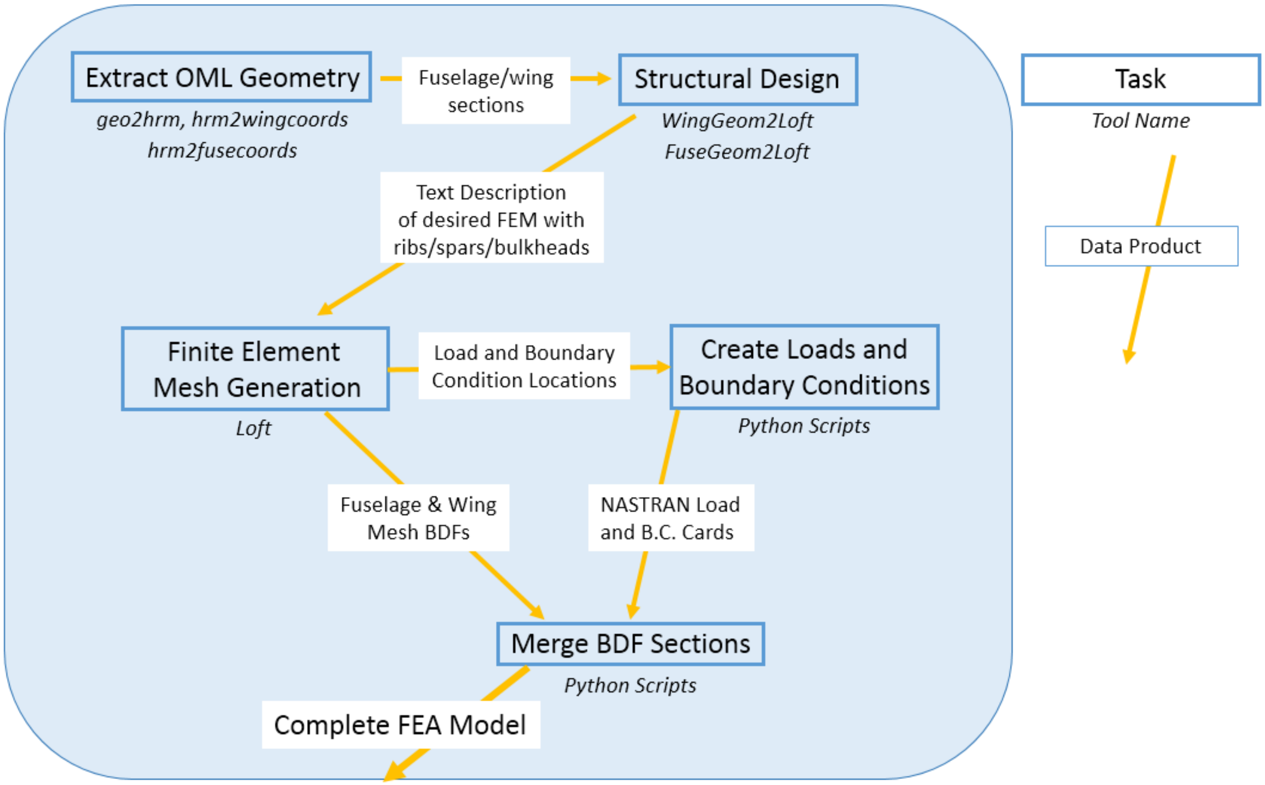


Figure 2: Flow chart illustrating rapid FEA model creation.

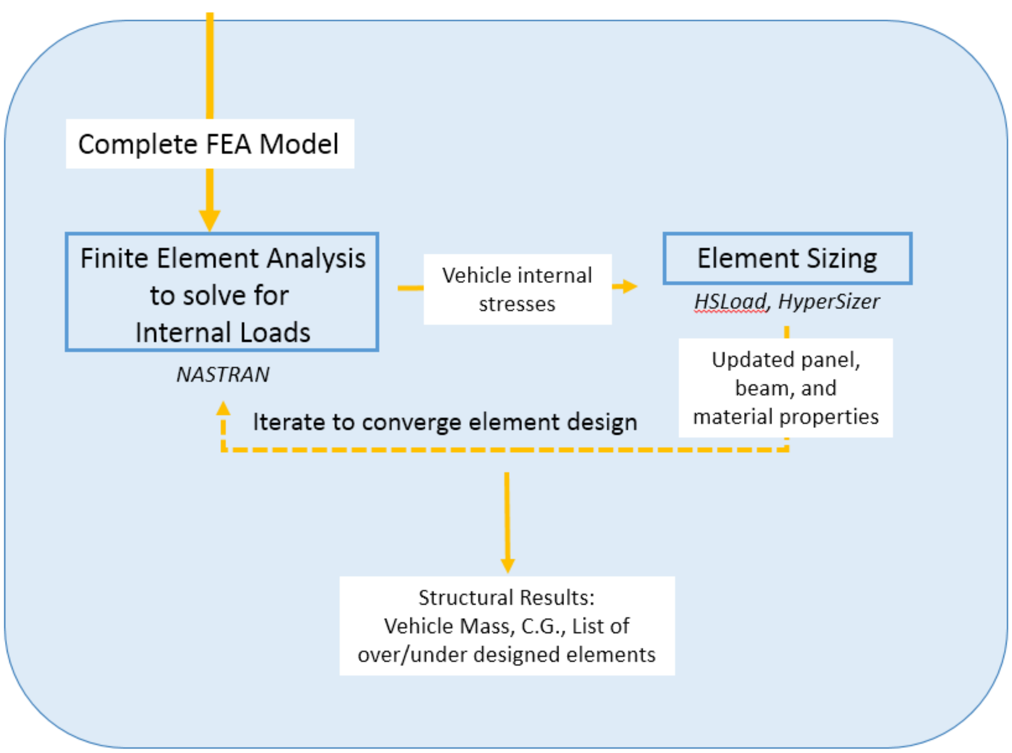


Figure 3: Flow chart illustrating rapid FEA model sizing.

A key feature of the conceptual design process is the ‘geo2hrm’ module. This module can transform the OML geometry information, regardless of its origin, into a format required by each of the disciplinary analysis modules. This greatly improves the consistency of the analysis results and removes many sources of uncertainty and human error.

The first step of the rapid FEM generation is geometry extraction. For now, only the wing and the fuselage geometry are extracted. These two components account for much of the total vehicle structural weight. Moreover, the weight of these components is difficult to predict without some form of sizing optimization.

Two codes are used to extract an approximation to the complex vehicle OML geometry created by ‘geo2hrm’. The first code, ‘Hrm2FuseCoords’, generates a file that contains the horizontal and vertical radii and vertical offset of the fuselage at arbitrary axial stations. The second code, ‘Hrm2WingCoords’, describes the vehicle wing at a series of arbitrary spanwise stations. At each station, the coordinates of the leading and trailing edge and the maximum thickness of the section are supplied. Note that no other airfoil data is provided; the rapid modeling approach assumes a simple symmetric 4-Digit NACA cross section with the thickness extracted from the geometry. This approximation is sufficient to capture wing sweep, angle of attack, dihedral, and twist. A more precise airfoil geometry would be required to improve volume estimates or to predict aerodynamic loads, but these features are not implemented yet.

The user is able to request any desired number of cross sections from the geometry modules. Thus, the user can improve the quality of the geometry approximation at the cost of increased computer processing time. The two geometry codes will select locations for the cross sections that best capture the inflections in the wing or fuselage shape. To do this, the codes will provide either the specified number of cross sections or a slightly higher number if the component has a lot of curvature that needs to be captured. Figures 4 and 5 illustrate typical fuselage and wing geometries extracted by this process.

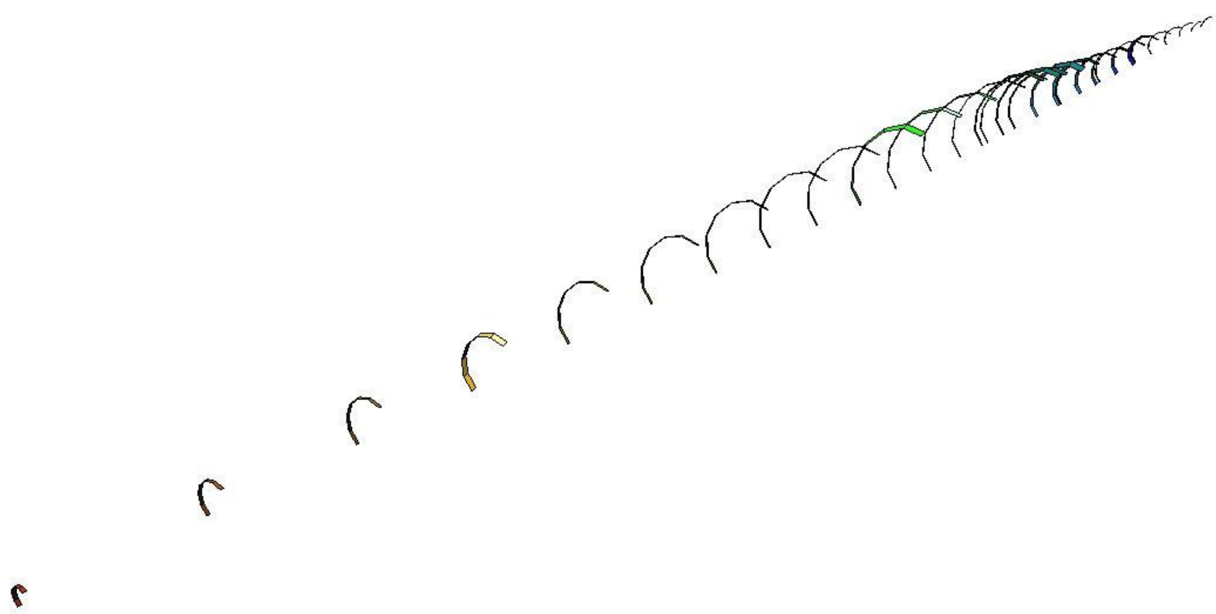


Figure 4. The fuselage geometry extraction step generates fuselage width and height at arbitrarily spaced stations.

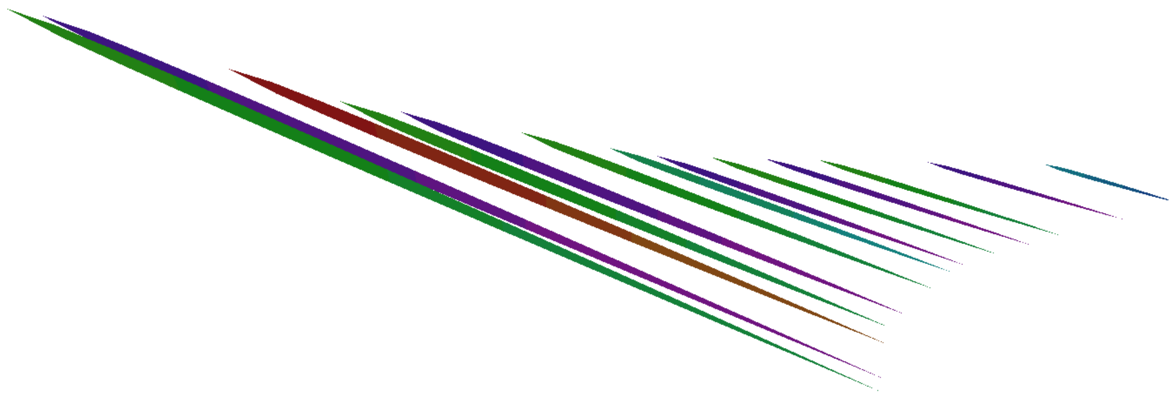


Figure 5. The wing geometry extraction step specifies leading and trailing edge locations and thickness at arbitrary spanwise stations.

2.2 Structural Layout

The second step of FEM generation is the structural layout. Two codes read the simplified geometry that approximates the OML of the fuselage and wings and create a structural design based on that geometry. These codes capture the structural design intent of the team. The codes have an extensive set of options for rib, spar, and bulkhead positions as well as for mesh density, airfoil selection, and fuselage cross sectional shape. A simplified set of options is exposed to the user in the ModelCenter framework. The two codes, 'WingCoords2Loft' and 'FuseCoords2Loft', read the extracted geometry descriptions as well as the user-chosen design options and create text input files describing the desired FEM that the meshing tool will create. The two codes are sufficiently general that the fuselage code could be used in the future to model nacelles and the wing code could be used to model tail or canard surfaces. These additional steps are not currently available in the rapid modeling subprocess but may be added in the future. The necessity of these secondary structures in preliminary sizing and ranking of candidate designs is felt to be low, but they could be added if that engineering judgement changes.

The fuselage modeling tool approximates the fuselage structure as a series of linearly interpolated sections between each supplied geometric cross section. Cross sections can have different horizontal and vertical radii as well as vertical offsets. Currently all cross sections are modeled as ellipses although other shapes are supported. The nose and tail of the fuselage taper to a sharp point as is appropriate for a supersonic vehicle. Solid bulkheads can be requested at arbitrary axial stations. These are used to attach the wing spars and to apply loads and boundary conditions at the landing gear stations.

The wing modeling tool approximates the aircraft wing structure as a series of spanwise trapezoidal sections between two consecutive supplied wing cross sections as seen in figure 6. The model captures sweep, taper, angle of attack, dihedral and twist. Ribs can be specified at desired spanwise percentages and spars are specified at desired chordwise percentages. The 'WingCoords2Loft' code converts the global rib locations to local percentages on particular trapezoidal sections. For a conventional transport wing, this approach produces a reasonable conceptual layout for its internal structure. However, for a wing that is built from many narrow trapezoidal sections, this approach can produce curved spars. The spars can be meshed, analyzed, and sized, but they are not particularly representative of current construction practices. It is likely that a wing with curved spars will incur an extra weight penalty. This penalty has the desired effect; it will rank the wing with highly curved spars as less desirable than the wing with straight spars.

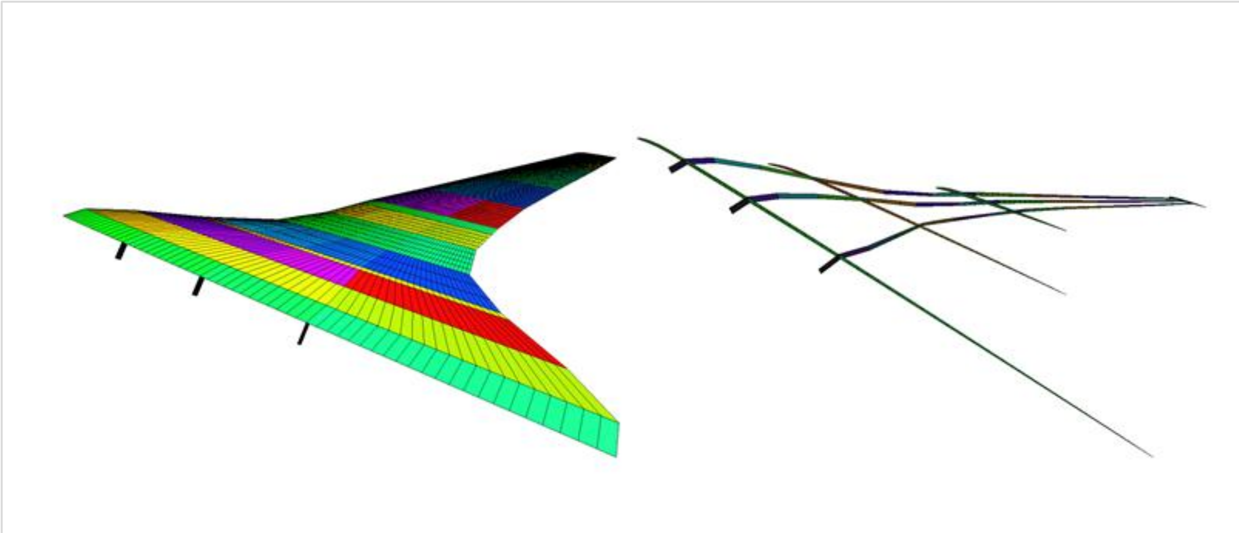


Figure 6. Piecewise-trapezoidal wing sections and curved spars.

The rapid structural design process can have issues with wings that come to a point at the wing tip (have zero chord) as seen in figure 7. The meshing tool creates several degenerate quad elements consisting of three nodes rather than four. The ‘WingCoords2Loft’ tool addresses this problem by truncating the wing and generating one fewer section. Since the wing tip is very small and lightly loaded, ignoring this final section has an insignificant effect on the structural analysis results.

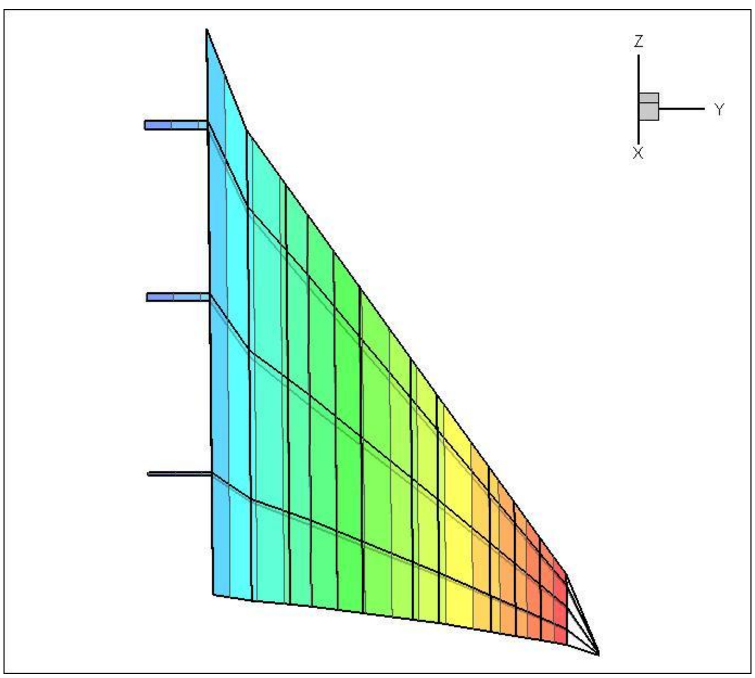


Figure 7. Wing FEM before (white) and after tip truncation (colored).

2.3 Generating FEA Mesh

The structural analysis meshing tool at the core of the rapid modeling approach is the NASA-developed program called Loft (ref. [9]). Loft is a parametric mesh generating code for stiffened shell aerospace vehicles. It has been used to model objects as diverse as launch vehicles, hypersonic orbiters, and lunar landers. It reads a text input file describing the geometry and the mesh details desired and generates finite element meshes in a wide variety of formats including Nastran bulk data file (BDF) and graphics formats (Tecplot) as seen in figures 8 and 9.

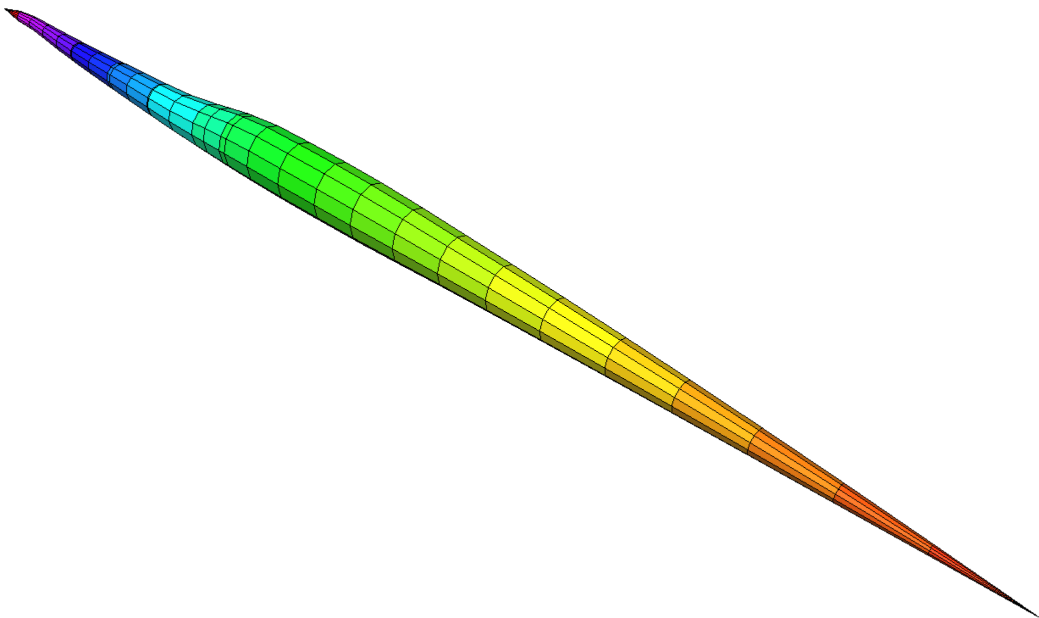


Figure 8: Loft creates an FEA fuselage model based on approximate geometry.

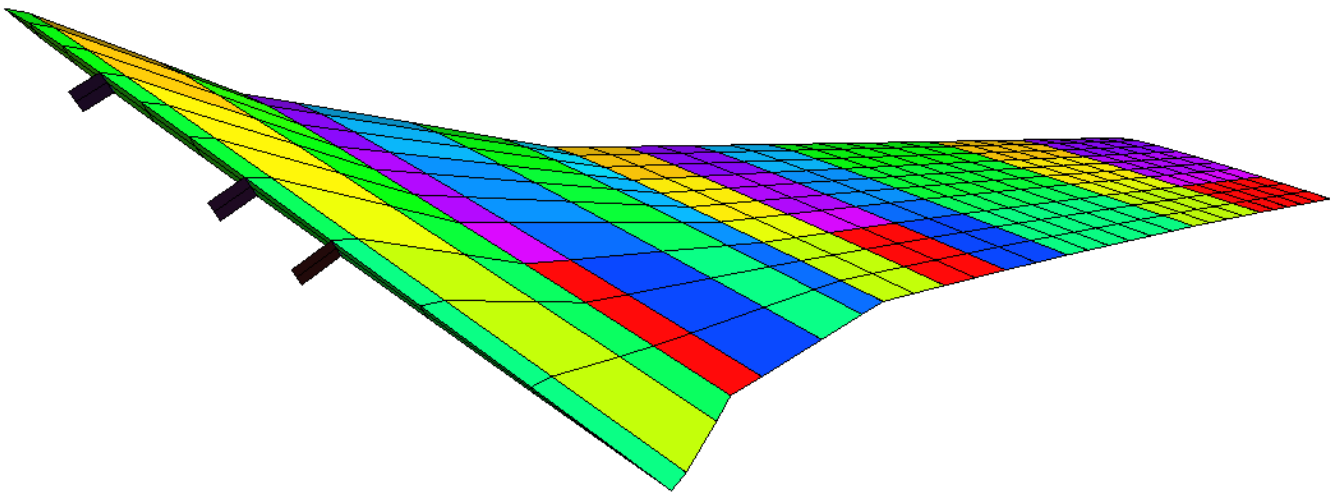


Figure 9: Loft creates an FEA wing model based on approximate geometry.

Loft automatically makes elemental property assignments that are appropriate for sizing. These properties are given user-defined names that make post-processing and manual operation much easier. Rather than reporting that shell element 30001 has a negative margin the software reports that "Wing Section 1-Skin Upper" has a negative margin.

Loft has a powerful "region" mode that facilitates load set and boundary condition generation. The input file created by WingCoords2Loft instructs Loft to create files containing a list of elements and node numbers on the wing upper and lower skins so that lifting pressure can be applied to each element. The internal math and variable functionality in Loft is used to compute both the planform area of the wing, and the uniform pressure required on the skin upper and lower surfaces to provide the lift specified in the design flight load cases. In the future, a similar procedure could transfer a more accurate pressure distribution derived from wind tunnel measurements or CFD analysis.

During the Loft input file creation, the user can control the location of spars, ribs, and landing gear and the density of the mesh to be created. After the fuselage and wing meshes are created, a series of scripts are run to assemble a complete Nastran BDF. These scripts are also used to create boundary conditions and load set definitions and to merge them with the Loft-created mesh to create a full model.

The scripts that drive the generation of the wing and fuselage meshes automatically create a wing carry-through that extends the main wing spars (e.g., see figs. 7 and 9). These scripts also create fuselage bulkheads at the spar locations and at the nose gear and main landing gear locations. As part of the Loft mesh generation process, region mode commands are given to create text files that list the assigned Nastran property numbers for the spar extensions and the fuselage bulkheads. An additional script then creates Nastran cards that glue the corresponding spars and bulkheads together and produce a single vehicle model.

2.4 Load Cases and Boundary Conditions

Two critical load cases are included in the rapid approach. A level cruise condition is modeled with uniform pressure over the wing upper and lower surfaces. A 2.5g runway bump is also created with constraints applied at the landing gear support locations. Together these two cases capture representative critical loads on both the wing and the fuselage and can be used to perform structural sizing for the simplified model. Initial testing indicates that this method for creating load cases can properly rank candidate concepts that are generated during multidisciplinary optimization.

Symmetric boundary conditions are applied to every node on the aircraft plane of symmetry. Extra boundary conditions are applied at the two fuselage bulkheads that support the nose and main landing gear. The Nastran permanent glued contact feature is used to determine multi-point constraints that attach the wing spars to the fuselage bulkheads. Figure 10 shows part of an automatically-created FEA model indicating single point constraints (symmetric boundary conditions) in blue and multipoint constraints (spar/bulkhead gluing) in pink.

After the load cases and boundary conditions are defined, the process creates a set of Nastran BDF files that contain the fuselage mesh, the wing mesh, the design load cases, and the boundary conditions. A master model file is then created that references each of these BDF files using the Nastran "include" instruction. This master file is a complete, analyzable, finite element model of the simplified vehicle. However, the material properties and the panel and beam dimensions in the FEA model have notional minimum values and need to be updated with the sizing optimization.

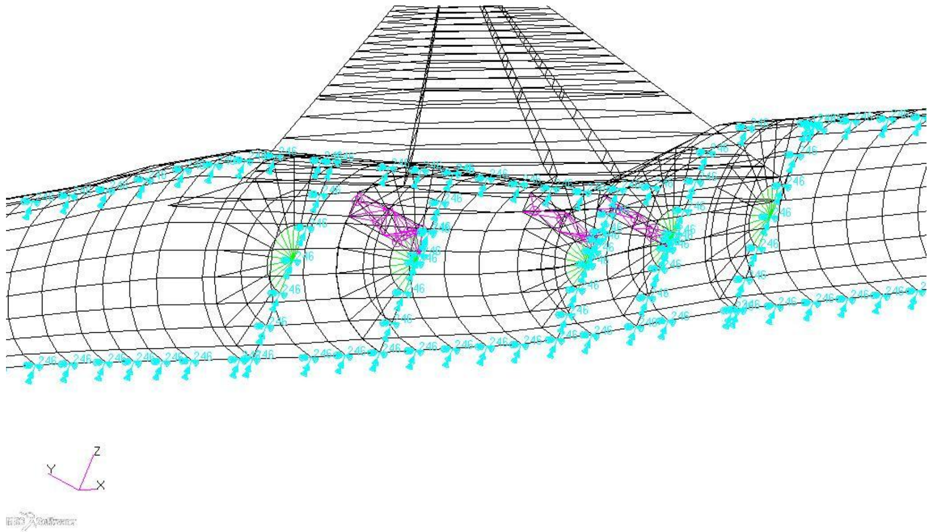


Figure 10. Constraints applied to typical supersonic FEA model.

2.5 Structural Optimization and Material Selection

The FEA model created by Loft assumes a constant thickness and uniform material properties for all structural elements. A sizing optimization must be performed to change the panel designs until the weight of the vehicle is minimized and all load case constraints are satisfied. The generated model is first analyzed using Nastran static analysis. This analysis computes the internal forces on each element for each load case. Next, HyperSizer® (ref. [10]), a product of Collier Research Corp., is used to compute the required panel and stiffener thicknesses to resist the internal forces in each part of the vehicle.

A code called HSLoad incorporates the sizing operation into the ModelCenter framework. This code, developed at NASA Langley, accesses HyperSizer's COM Application Programming Interface (API) and instructs HyperSizer to load the Nastran model, select design options, perform a sizing optimization, and report results. HSLoad converts the GUI-based HyperSizer software into a code suitable for batch operation.

The user may interact with the HyperSizer GUI to choose design variables and select structural concepts. These decisions are stored in design templates within HyperSizer which calls them "stored global designs". These template families are chosen by expert users and HyperSizer is instructed by HSLoad to size the vehicle based on the chosen approach.

The usefulness of the sizing optimization results depends on decisions made by the expert user. For example, the user can choose stiffened or unstiffened panels for wing and fuselage skins. The appropriate minimum gage for these panels depends on the size and weight of the vehicle. The user can specify an all aluminum structure or can allow HyperSizer software to choose from a range of metal and composite materials. The user can set the buckling length scales or allow HyperSizer to set these scales based on the FEA mesh size. Finally, the user can restrict the maximum thickness of elements based on the volume inside the wings and fuselage, or can allow HyperSizer to pick whatever thickness is needed to satisfy the constraints. In fact, any of the features of the HyperSizer design software available through the HyperSizer API can be made accessible by modifications to the HSLoad program.

When HyperSizer sizing analysis is complete, HSLoad performs post-processing tasks that report the vehicle weight, a list of elements that have negative margins, and a list of elements that are at minimum-gauge. A second run of Nastran static analysis is performed to compute the CG location and maximum displacements of the sized vehicle. Additional iterations between HyperSizer and Nastran codes may be performed to produce converged results. This iteration is recommended due to changing inertial loads and load paths as the sizing program adjusts panel designs and thicknesses across the vehicle.

3 Evaluation of Rapid Structural Analysis Approach

The rapid structural analysis subprocess has been successfully tested on about two dozen supersonic aircraft concepts generated by a conceptual design team. Moreover, the subprocess operated successfully as part of a DOE iterative analysis with 200 cases. All of the concepts tested were somewhat similar to the LBFD concept pictured in figure 1. In this section, the advantages of the automated subprocess are explained and some examples are provided. The evaluation of the rapid approach uncovered roadblocks that prevent the subprocess from being 100% satisfactory. In this section, those roadblocks are noted, the current state of the software is reported, and opportunities for improvement are suggested.

3.1 Software Framework

The software framework approach has many advantages. First, it is a modular approach and therefore new features such as modal analysis would be easy to add. Second, it is a “plug and play” approach and therefore concept designers can choose the set of modules that they require. Third, it is a repeatable process and therefore a few top level variables describe the current concept. Fourth, the software framework improves the consistency of results. If all the disciplinary modules are linked together, then each will treat the same geometry and the same flight conditions based on changes to the top level parameters. Finally, software issues are addressed. Any software bugs or linking errors found by one user are fixed in the framework and are thereafter used by everyone. Similarly, the integration of each software package into the framework is accomplished once and then will be applied to each new concept in a consistent manner. Updates can be performed as new versions of the software become available, thus enabling all users to execute the same version of the code.

Many of the features that make software frameworks attractive for conceptual designers are a mixed blessing for module developers and software testers. For one thing, designers rightfully complain if a new analysis capability doubles the cycle time, requires unusual inputs, or halts their processing. Designers want all errors to be fixed as soon as they are discovered. On the other hand, software testers want any errors that they observe to be due to their own modifications. Thus, testers often desire a protected version of the conceptual framework, and consequently miss out on error fixes, software updates, and the newest concepts. This is problematic because module developers desire representative input values and a workable geometry and thus desire a mature conceptual design. Developers need a mature design because the inputs that are critical for structural analysis may not be important inputs for other analyses and therefore are decided later in the design cycle. This is certainly true, for example, in the location of the main landing gear which affects many load cases and influences the internal skeleton but may not be carefully specified until the aircraft design matures.

The ModelCenter framework is a good choice for the conceptual design process. The framework can link analysis modules that exist on several different machines with different operating systems; thus, Nastran software runs on a Linux server while the HyperSizer GUI runs only on Windows servers. The framework can more efficiently parse selected values such as weight and CG from a lengthy Nastran output file. The framework allows the module developer to work on a frozen version of the process. Once a improved module has been validated to perform as designed, the developer can then insert his modified subprocess into the version used by all designers.

One framework issue that remains unresolved has to do with iterations. For example, figure 3 indicates an iteration between HyperSizer optimization and Nastran static analysis that continues until the internal forces and the element sizes are not changing very much. The ModelCenter framework includes a converger module that will change input values until the output values converge. This approach can be implemented as soon as an appropriate convergence criteria is agreed upon.

3.2 Parametric Geometry and Meshing Controls

Conceptual designers consider a wide range of geometries including some OMLs automatically generated by design of experiments (DOE). Two of these interesting geometries are pictured in figure 11. All have been successfully analyzed by the rapid FEA subprocess using Loft FEA mesh generation. Such a large OML change would challenge any automated remeshing or mesh morphing technique.

Depending on the method used to parameterize the geometry, some OMLs are described by a few cross-sections and some OMLs are described by hundreds of cross-sections. Both computer processing time and mesh quality could be adversely affected when given too many or too few cross-sections. This difficulty is addressed by having a geometry extraction step with proper user controls.

There is no guarantee that a particular concept is buildable and there is a high probability that some concepts generated by a DOE will be infeasible. A primary reason for including structural analysis in the conceptual design process is to identify poor structural layouts during DOE or optimization iterations. Plots such as those included in figure 11 are one way to identify undesirable concepts. Other methods of comparing one concept with another can be based on structural weight, wing tip deflection, CG location, or margin of safety. For example, Nastran software reports CG location and deflection maximums. HyperSizer software estimates structural weight and identifies elements with low margin of safety. Such outputs can be combined to form effective ranking measures for a genetic algorithm or DOE.

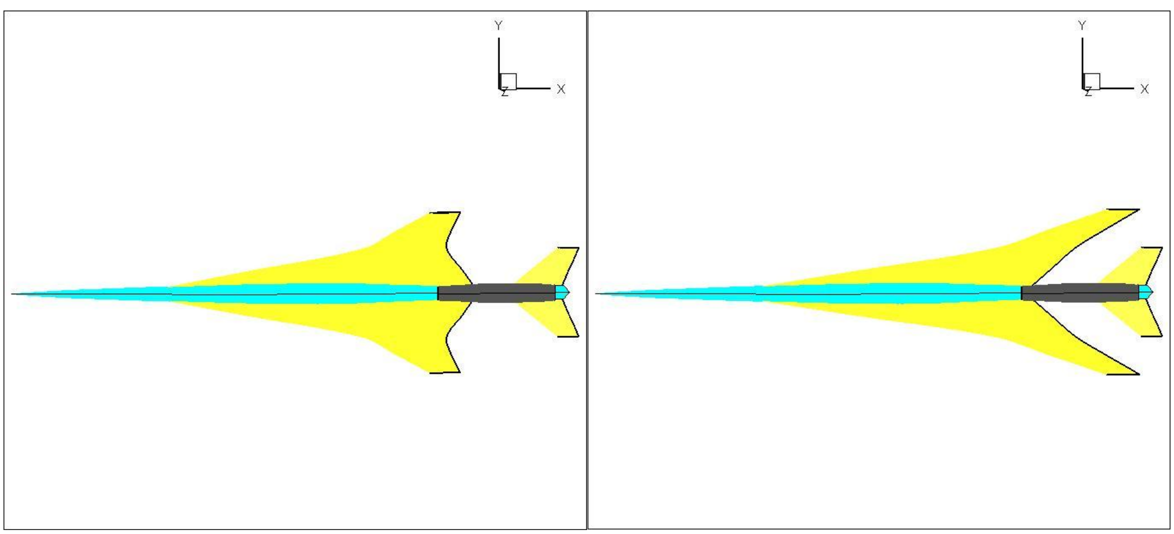
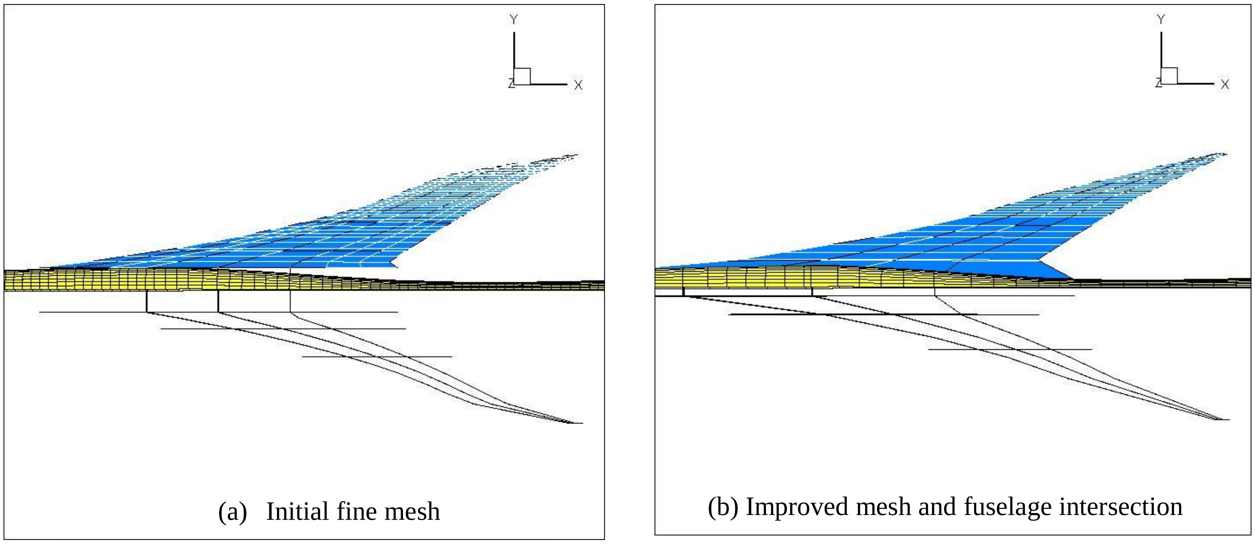


Figure 11. OML examples generated by DOE.



(a) Initial fine mesh

(b) Improved mesh and fuselage intersection

Figure 12. An atypical wing illustrates mesh and intersection adjustments.

Parametric geometry that is perfectly adequate for most parts of the conceptual design process can cause difficulty for the structural analysis subprocess. For example, the OML geometry available from VSP or Jaguar defines cross-sections of each existing aircraft component such as the wing or fuselage. However, the intersection between any two components (or lack thereof) can be difficult to determine. As a second example, the OML geometry can specify 3-D cross-sections that collapse into a line or a point (recall fig. 7). Moreover, unusual wing planforms with a lot of twist and dihedral can generate odd looking ribs and spars (recall fig. 6). If a wing carry-through structure is too thin or a fuselage nose collapses to a line then the FEA process will fail. Ideally, the subprocess would detect these errors and provide knowledge-based solutions to avoid them. For now, the user is provided with plots and warning messages to diagnose problems and with controls to circumvent known parametric geometry issues.

The current rapid FEA subprocess allows some user control over each new concept. For example, the user can decide whether the engine nacelle is actually part of the fuselage or should be modeled as a separate structure. The user can modify the landing gear position and internal wing layout. Figure 12 illustrates the effect of Loft inputs such as mesh density and rib and spar positions. These controls are intuitive and are aided by the automatically generated plots (e.g., figure 12). For the most part, the default values for each user input produce a good internal structure that can be adjusted after checking the initial layout plots.

3.3 Structural Sizing

The rapid structural analysis subprocess creates a structural skeleton composed of ribs, spars, wing upper skin, wing lower skin, and fuselage skin. Each group is modeled as unstiffened panels or sandwich panels. Only bulkheads are modeled as grid stiffened panels. This means that the number of design variable combinations is small and the HyperSizer optimization runs quickly. A complete iteration from Loft to Nastran to HyperSizer software takes about two or three minutes.

The accuracy and time spent on each HyperSizer execution depends on the number of design variables specified and on the quality of the initial design decisions. For example, consider the HyperSizer sizing input form pictured in figure 13. Each of the five bulkheads is modeled as a grid stiffened panel and each panel is described by eight HyperSizer design variables. Each design variable can take on a few discrete values. Notice in figure 13 that the thickness of the top face is one design variable that can take on 5 values between 0.05 and 1.5. Another design variable controls the choice of materials (see the bottom of Fig 13). There are 9000 possible combinations for setting the design variables values in the Bulkheads group. However, HyperSizer does not have to analyze all possible combinations. Rather, the optimization process analyzes the combination with the minimum weight and subsequent iterations utilize increasingly heavier combinations until all bulkheads have a positive margin of safety. Thus, the speed of optimization will increase if the number of combinations is reduced, or if the minimum weight combination is feasible for many of the elements in each group.

The current philosophy is to use generic HyperSizer input settings for every aircraft concept. If a concept looks particularly attractive, then a knowledgeable person can adjust the HyperSizer inputs to increase confidence in the weight and CG estimates. A better plan for expert knowledge integration would be to give every ModelCenter user some control over HyperSizer inputs or to create several knowledge-based templates and select the best one based on fuselage length or the target weight of the vehicle.

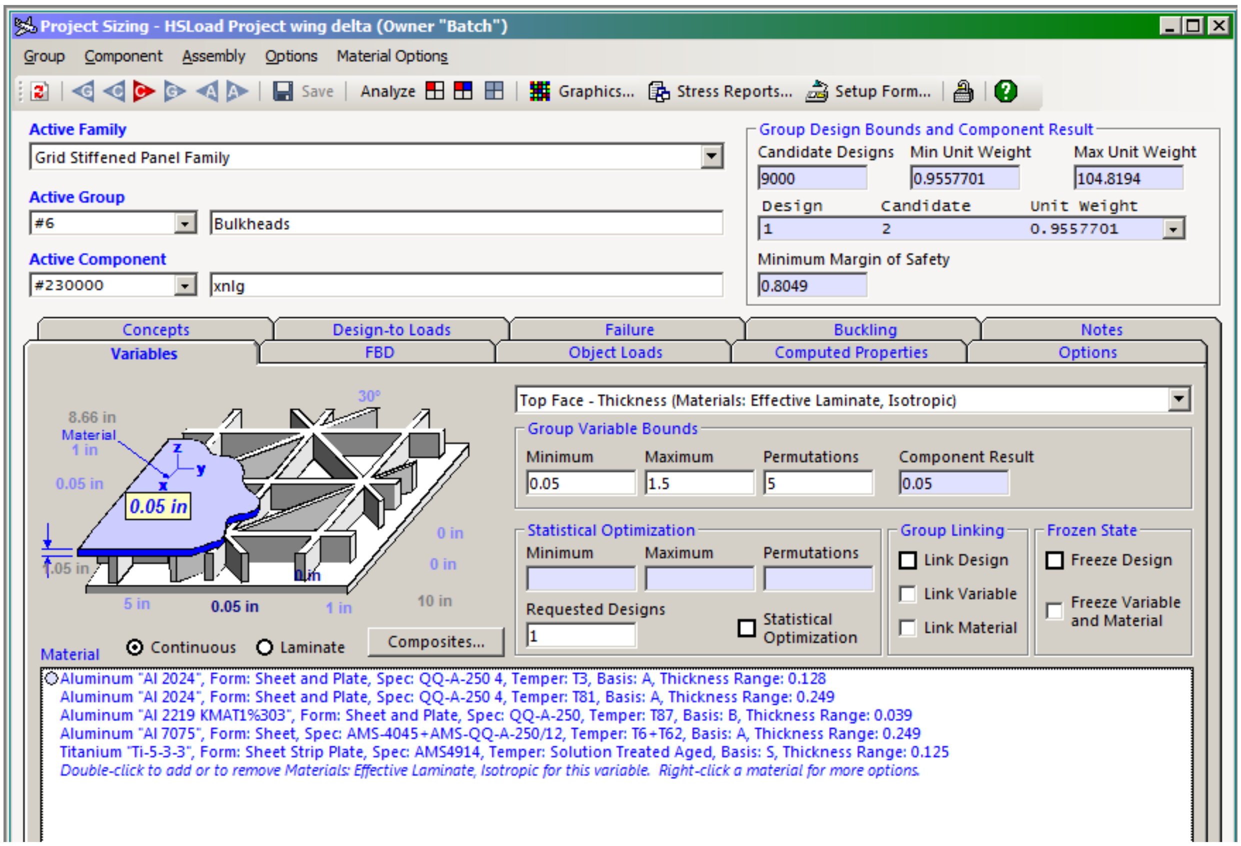


Figure 13. Screen shot of Hypersizer sizing form for grid stiffened panels.

4 Case Studies

4.1 LBFD Concept

The low-boom flight demonstrator concept shown in figure 1 and described in reference [5] was used as a case study to test the structural analysis subprocess. This was a mature concept that included inviscid

CFD results, fuel tank layouts, and estimates for the weight of engine, landing gear, and cockpit based on available hardware. A structural FEM of the entire vehicle was manually created and was used to assess the results of the rapid FEA subprocess.

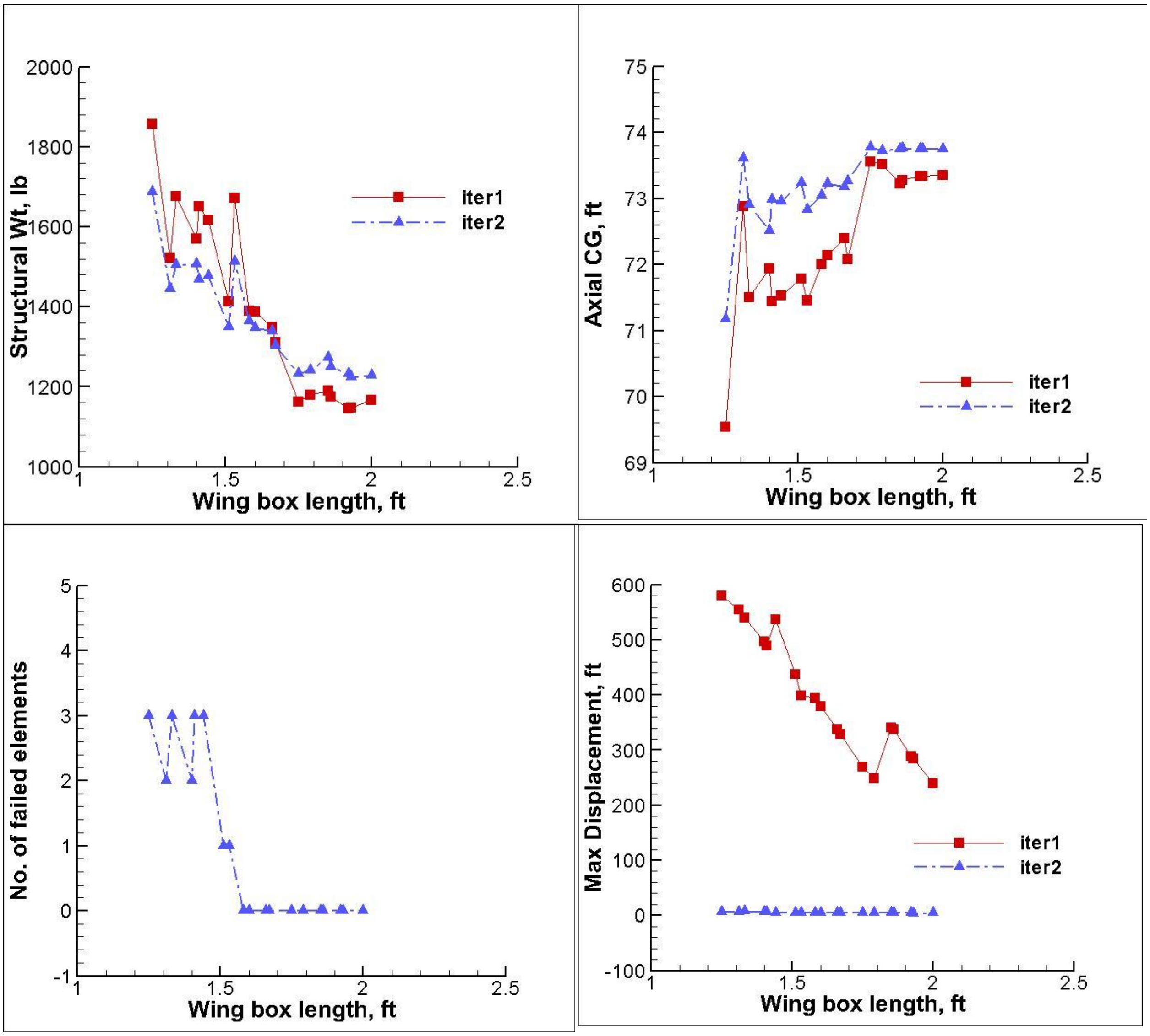


Figure 14. DOE results for iteration 1 and 2 of Nastran analysis and HyperSizer optimization.

The reliability of the FEM generation process was tested by running a DOE in the ModelCenter framework. The two design variables are similar to the ones that produced figure 12. One variable (box_loc) moves the first rib away from the fuselage so that the wing box is longer and the wing skin is shorter. The other variable (spar1) moves the first spar to a new percent chord location. Of the two variables, ‘box_loc’ proved to be much more influential.

The DOE created and analyzed 19 cases using a Latin Hypercube design to randomly set 'box_loc' and 'spar1' values. The process automatically generated a Loft mesh followed by two iterations of Nastran analysis and Hypersizer optimization. The average analysis time is about 6 minutes per case. The DOE results reveal that there is a large difference between the Nastran results after one sizing iteration compared to results after the second sizing iteration. Additional iterations did not change the FEA results for this concept.

Figure 14 contains typical results. In each plot, the red squares correspond to the first iteration and the blue triangles correspond to the second iteration. The maximum displacements for the first (red) iteration are very large. This is expected since some of the default thicknesses of the elements will be too small to carry the loads on them. We have more confidence in the results for the second (blue) iteration, as this iteration is the first analysis where structural components are generally sized for expected loads. For wing box lengths less than 1.5 feet Hypersizer warnings were generated. Insufficient contact between the spar and the bulkhead (when the wing box is short) causes these warnings (recall Fig. 10). In such a case, the optimization will make both spar and bulkhead thicker and will increase the structural weight but will not resolve the root cause of the problem.

This initial small DOE test case demonstrates the range of outputs possible from a single supersonic aircraft concept. Reliable outputs are possible but only after several iterations between Nastran analysis and HyperSizer optimization. Furthermore, if the converged solution still reports failed elements or Nastran analysis reports large maximum displacements, then the user can attempt to improve the inputs to the FEA subprocess or can consider that concept to be structurally infeasible.

4.2 Variable Geometry Concepts

The robustness of the FEM generation process was tested using a more extensive DOE. This second DOE generated 200 configurations based on the wing section inputs shown in figure 15. In this case, only one iteration of HyperSizer optimization and Nastran reanalysis is used to reduce the execution time. Each new configuration had a completely different wing planform shape as indicated by representative top views shown in figure 11. The FEA subprocess input parameters for the baseline configuration were selected to avoid any issues with wing box length or poor rib and spar placement.

The results of this DOE were very encouraging. The automated structural analysis and sizing optimization were executed for all 200 configurations without errors. The configurations had a wide range of structural weights, maximum deflections, and CG values. Spot checking of the outliers indicated that this sort of DOE could help to identify concepts with undesirable structural properties. Thus, the rapid structural analysis subprocess could be used to rank concepts or to form constraints for a multidisciplinary optimization process.

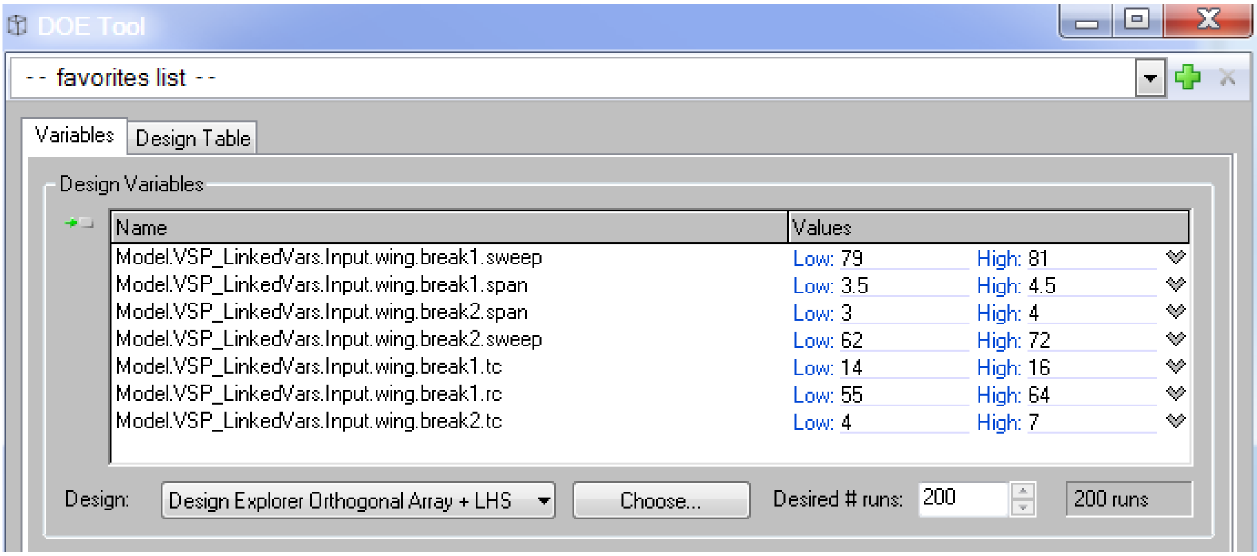


Figure 15. Screen shot of ModelCenter DOE input form.

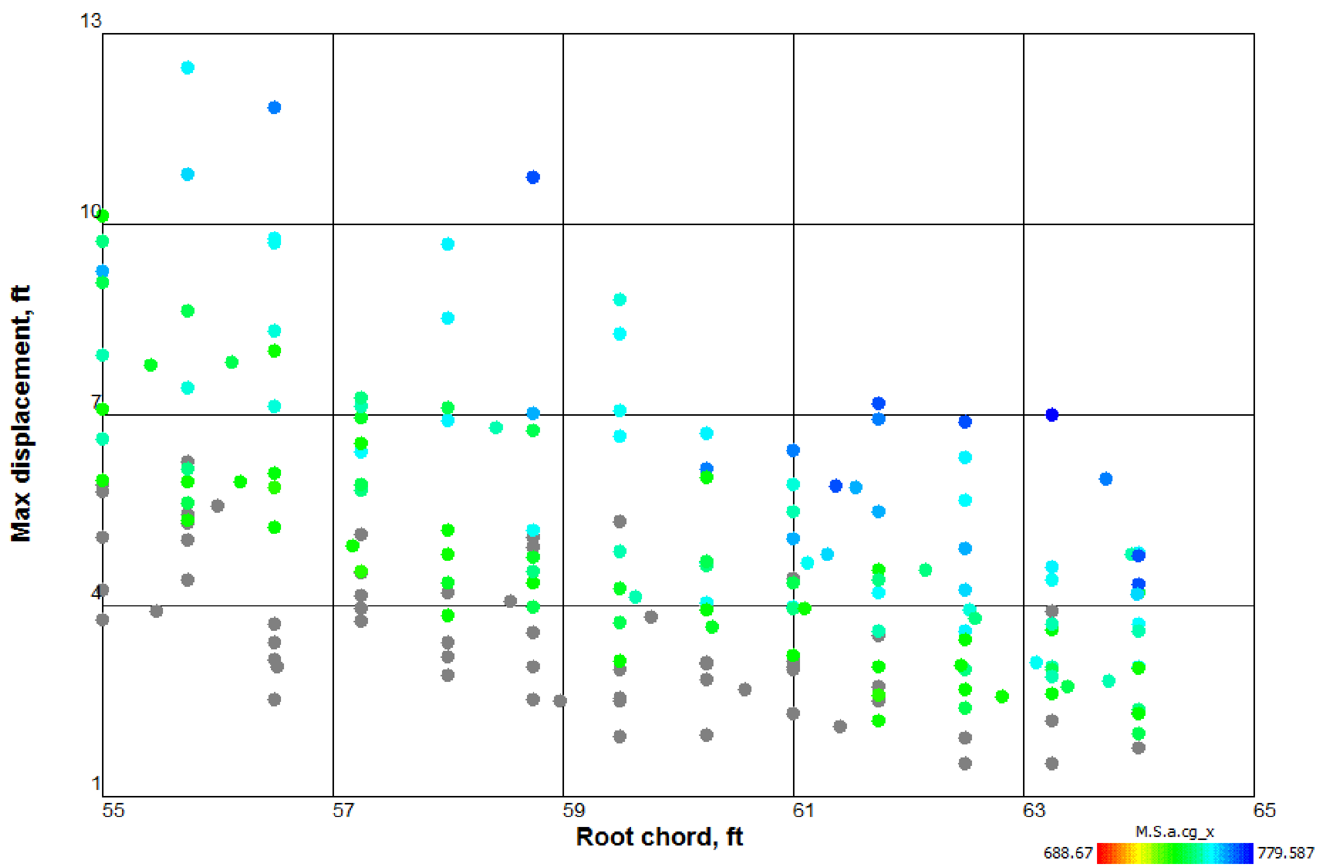


Figure 16. Maximum wing tip deflection as a function of root chord length.

Figures 16 and 17 present typical results from the 200 configuration DOE. These scatter plots are one of several data visualization tools available in the ModelCenter GUI. The scatter plots enable the user to extract two dimensional slices from a multidimensional data space. Each colored dot corresponds to one aircraft configuration. Any configuration of interest can be loaded individually for further examination (see figure 18).

Figure 16 displays two types of data for each configuration after one iteration of HyperSizer optimization and Nastran analysis. The vertical location of each dot indicates the maximum displacement and the color of the dot indicates the CG location. As expected, the maximum wing tip deflection decreases as the length of the root chord increases. However, the geometry of the wing also affects the axial location of the aircraft CG. Grey colored dots indicate infeasible configurations where the CG is too far forward. Blue dots indicate favored configurations where the CG is farther aft.

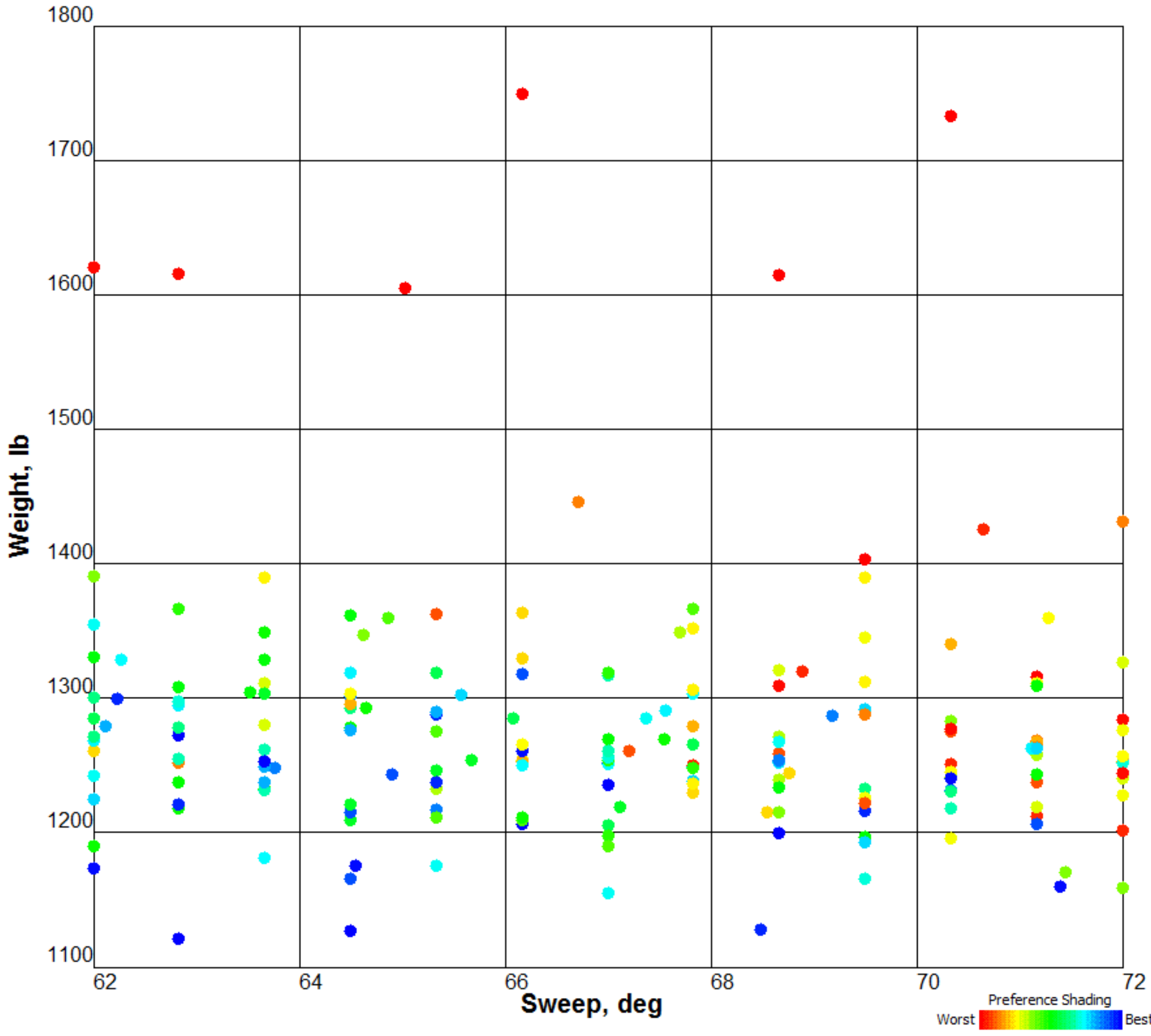


Figure 17. Optimized structural weight as a function of outboard wing sweep.

Figure 17 displays information about optimized wing and fuselage weight as a function of the outboard wing sweep angle. Notice that several configurations have much higher than average weight. These outliers can be studied in more detail and the design variable values attached to these high weight configurations can be excluded from further multidisciplinary analysis.

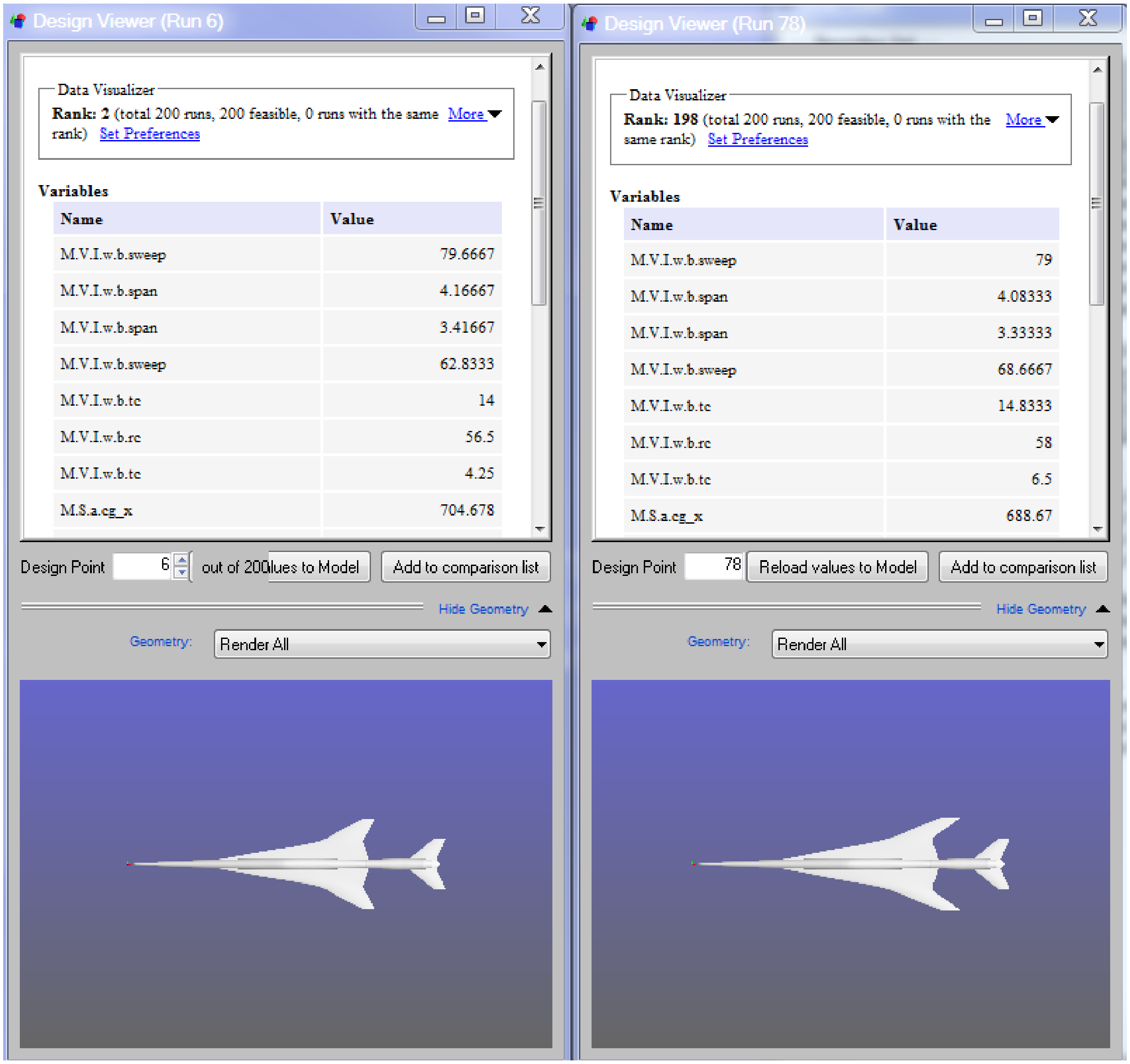


Figure 18. Snapshot of a high ranking design (left) and a low ranking design (right).

The results in figures 16 and 17 illustrate the need to consider structural weight and wing deflections and axial CG simultaneously. Preference shading is one way to accomplish this goal. The data visualizer tool in ModelCenter framework allows the user to change the weighting on each output quantity and to combine outputs into a new objective function. For example, in figure 17, weight and CG and max displacement are combined. In this figure, red dots correspond to the worst configurations and blue dots correspond to the best configurations. Thus, the dark blue preference shading indicates configurations with low weight and low maximum displacement that have a CG near the aerodynamic center of the aircraft.

With this added information, it is clear that reducing outboard wing sweep produces better designs. Figure 18 contains examples of one of the best configurations (outboard sweep = 62.8 ft) and one of the worst configurations (outboard sweep = 68.7 ft).

Insights such as those gained from figures 16-18 can be very valuable during conceptual design of a supersonic aircraft. The structural weight, maximum deflection, and CG do not have to be especially accurate in order to guide the designer towards good designs and away from problematic designs. Moreover, these computed parameters are rigorous, physics-based, and repeatable metrics that result in dependable indicators of configuration merit. This new capability allows the designer to consider structural constraints at a much earlier stage in the design cycle. Figures 16 and 17 represent new information that has rarely been available to conceptual designers. The fact that each point in the figure was created automatically in a few minutes further increases value and practicality of this conceptual design information.

5 Concluding Remarks

The objective of this effort was to uncover potential structural design issues at an earlier conceptual design stage. A new structural analysis subprocess has been added to an existing conceptual design framework. This capability creates a finite element mesh, representative load cases, and optimized element sizing in a more rapid, automated, and robust manner than prior methods in use at NASA.

The rapid and robust subprocess was tested for a wide range of supersonic vehicle geometries. Any concept can be studied in a few minutes; plots of the rib and spar locations and estimates of the wing and fuselage weight help to choose between competing concepts. The current version now permits the internal structure of a new concept to be adjusted with greatly reduced set of intuitive user inputs. Several dozen supersonic concepts have been successfully tested to verify the performance and results of the subprocess modules.

This capability provides information that has, until now, rarely been available to conceptual designers. Initial testing in conjuction with a low-boom supersonic flight demonstrator concept development was shown to illustrate its value and argues for continued improvement and validation of this methodology.

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14. ABSTRACT

This paper describes a multi-year effort to add a structural analysis subprocess to a supersonic aircraft conceptual design process. The desired capabilities include parametric geometry, automatic finite element mesh generation, static and aeroelastic analysis, and structural sizing. The paper discusses implementation details of the new subprocess, captures lessons learned, and suggests future improvements. The subprocess quickly compares concepts and robustly handles large changes in wing or fuselage geometry. The subprocess can rank concepts with regard to their structural feasibility and can identify promising regions of the design space. The automated structural analysis subprocess is deemed robust and rapid enough to be included in multidisciplinary conceptual design and optimization studies.

15. SUBJECT TERMS

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