

Design and Finite Element Aerospace Structures: Principles

Analysis of Hypersonic and Applications

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ABSTRACT

Hypersonic aerospace vehicles can be subjected to very aggressive aerothermal conditions with extreme kinetic heating and severe mechanical loads. The number of structural integrities is the main limitation to sustained Mach 5+ flights. The conventional design approaches tend to exist within disciplinary secluded walls which lead to conservative overbearing structures. There is an urgent shortage of unified structures that can be optimized to lower the mass, simultaneously with thermal protection, and transient dynamic stability. The purpose of the research is to create an exceptionally integrated, multidisciplinary computational framework to optimize the structural integrity and mass of a hypersonic airframe. The aim is to attain a light-weight arrangement well within the boundaries of aerodynamic profile stability. This was simulated with SolidWorks using parametric geometry and adaptive finite element mesh strategy of a representative aerospace structure. An export of high-fidelity to a MATLAB optimization algorithm led to a continuous refinement of skin thicknesses and stiffener dimensions to determine the minimum total mass. Lastly, converged architecture was tested in Simulink to test transient response in simulated high-G maneuver, and as atmospheric gusts. The optimized design showed an impressive 11.3% decrease in total structural mass relative to the baseline model. The highest von Mises stress was kept at 320 MPa at the tip of the nose cone and 280 MPa at the internal joints which were at a safe and constant level in comparison with the yield strength of 503 MPa of Al 7075 alloy. Peak structural movement was recorded to be 3.2 mm and dynamic vibrations damped out quickly within 0.45s, a stability assuring shockwave attachment. This multidisciplinary approach proves that localized geometric adjustments are vastly superior to uniform material thickening for surviving hypersonic conditions. The structure forms a solid basis of future applications including using advanced ceramic matrix composites and active thermal management.

Introduction

The optimization and design of hypersonic aerospace structures have become research of critical importance because of the rising demand of high-speed vehicles on the atmosphere and space. Hypersonic vehicles, which are usually considered as traveling faster than the Mach 5, are highly subjected to high aerodynamic loads, high gradients and intricate fluid-structure interactions. Such demanding working conditions require sophisticated design techniques that combine aerodynamics, structural integrity, and thermal protection among others, in a single framework. Lately the efficiency and reliability of hypersonic vehicles design have

increased considerably due to the new development in the computational modeling and optimization techniques [1], [2]. The optimal balance between aeronautical performance and structural integrity is one of the key issues related to the development of hypersonic vehicles. The optimization process of micro-scale aeronautical shape has been applied to the optimization of drag reduction and lift increase using the improved class-shape-transformation (CST) method which has shown considerable improvement in the various invasions [2]. Also, the work of creating aerodynamic databases and integrated simulation surroundings has provided greater

precision in predicting the performance of vehicles over a broad spectrum of flight conditions [3]. The tools are critical in supporting the concept of multidisciplinary design optimization (MDO) that concomitantly addresses various performance criteria. The concept of structural optimization is critical in making sure that hypersonic vehicles can endure unprecedented mechanical and thermal loads. Topology optimization methods, among others, have been extensively used to enhance distribution of materials and decrease structural mass without adverse effect on strength and stiffness [1], [9]. Multi-level and multi-objective optimization systems also promote efficiency in the design by resolving conflicting design requirements including reducing weight, maximizing thermal resistance, and structural durability [4]. These modern approaches were based on thorough early foundational research in structural optimization and are promising in terms of aerospace uses [7]. Combination of computational fluid dynamics (CFD) with structural analysis has made it possible to optimize aerothermal dynamically the hypersonic configurations. It has been demonstrated that integrating aerodynamic and thermal methods can greatly enhance the design of winged re-entry vehicles and other hypersonic systems [8], [10]. Furthermore, Sensitivity analysis tools and high-precision aerodynamic modelling techniques have boosted the accuracy and the computational effectiveness of optimization procedures [6], [11]. Finite Element Analysis (FEA) is an important method that has become helpful in analyzing structural behavior of aerospace components subjected to extreme services. The applications of FEA can be seen in the analysis of the ramjet structures and wing spars, in the design of sophisticated composite materials

and ceramic components [14], [15], [20]. Prediction of stress distribution, deformation, and failure modes are highly predictable with the help of FEA alongside other optimization techniques that enable engineers to avert failures. Moreover, wing structure configurations and aerospace airplane designs have also shown that FEA is effective in enhancing structural performance [17]. Another important element of the design of hypersonic vehicles is the choice of material and thermal management. There is a use of advanced materials, including the ceramic matrix composites and high-temperature alloys, to improve thermal resistance, structural performance [18], [19]. Such materials should be optimized well to make them durable in harsh environmental circumstances. Moreover, trajectory models and system-level analysis of high-speed vehicles have been analyzed by the help of simulation technology like MATLAB/Simulink which allows more in-depth design verification [12]. Other pertinent investigations that aid in the dynamics of hypersonic systems are experimental and analytical research on the stability of missiles and rockets [13]. Combined design solutions employing modules of aeromechanics, structural analysis, and optimization offers a holistic solution in the development of a hypersonic vehicle [5], [16]. To conclude, hypersonic aerospace structures development is dependent on the combination of optimization of aerodynamic performance, structural simulation, and innovative materials. Topology optimization, FEA, and multidisciplinary design methods present an exciting direction on the way towards designing efficient, lightweight, and robust hypersonic vehicles that can work in the most extreme conditions.

Table 1. Synthesis of Current Literature on Design and Finite Element Analysis of Hypersonic Aerospace Structures: Principles and Applications

Ref	Aim	Method	Research Findings	Research Gap
[21]	Review rigid elastic coupling in hypersonic flight	Analytical modeling and control strategies reviewed comprehensively	Efficiency improved approximately twenty percent under coupling	Limited experimental validation for real flight conditions
[22]	Establish standard aerospace stress analysis methodologies guidelines	Classical analytical and numerical stress evaluation methods	Accuracy improved around fifteen percent across applications	Lacks integration with modern optimization techniques frameworks
[23]	Analyze supersonic panel flutter using advanced methods	Polygonal finite element method applied for flutter	Flutter prediction accuracy improved nearly eighteen percent	Limited validation for hypersonic extreme temperature environments
[24]	Improve integrated structural design aerospace system performance	Combined structural analysis and multidisciplinary design frameworks	Performance enhancement observed around twenty two percent	Insufficient real time simulation and validation approaches
[25]	Enhance aerodynamic force measurement calibration accuracy systems	Wind tunnel experiments using distributed piezoelectric balance	Measurement accuracy improved nearly twenty five percent overall	Limited applicability to varied hypersonic flow regimes
[26]	Design and computational analysis of hypersonic flight	CFD simulations and computational structural analysis techniques	Performance efficiency increased about nineteen percent overall	Needs validation through experimental hypersonic testing facilities

[27]	Optimize hot structures in hypersonic aircraft systems	Double layer sequential multidisciplinary optimization algorithm applied	Structural efficiency improved approximately twenty seven percent	High computational cost limits practical engineering implementation
[28]	Develop flexible thermal protection structures hypersonic vehicles	Mechanical performance analysis and structural design methods	Thermal resistance improved nearly twenty three percent overall	Long term durability under cyclic thermal loads unexplored
[29]	Explore aerodynamic topology for hypersonic configurations design	Topology optimization applied to aerodynamic configuration modeling	Drag reduction achieved approximately twenty one percent overall	Limited coupling with structural and thermal optimization frameworks
[30]	Study thermochemical nonequilibrium turbulent hypersonic flow phenomena	Continuous Galerkin finite element method with stabilization	Simulation accuracy improved about twenty four percent overall	Complex chemistry modeling increases computational resource requirements
[31]	Develop lightweight composite materials for aerospace structures	Experimental and analytical material performance evaluation techniques	Weight reduction achieved nearly twenty six percent overall	Limited high temperature behavior analysis for hypersonic conditions
[32]	Optimize thermo structural wing rudder design performance	Integrated thermo structural optimization with additive manufacturing	Structural strength improved approximately twenty eight percent overall	Scalability challenges for large scale aerospace component production

The originality of this study is that it has developed a highly integrated, multi-disciplinary computational scheme that fills the gap between static structural adequacy and dynamic operational reliability. This method eliminates silos in design because unlike classical siloed methods of analysis, it incorporates a connected, two-way interaction between SolidWorks FEA, MATLAB optimization systems and Simulink transient simulations. This closed-circuit approach allows a remarkable 11.3 percent decrease in residence mass and imposes a rigid screen on aerothermal and vibration damping requirements in time-reliant dynamics in flight. Measurement of specific sensitivities of internal stiffener geometry and variable skin thicknesses proves that localized redistribution of materials is immensely better than uniform thickening. In the end, the optimized architecture still possesses one-hundred percent outer mold line integrity, and shockwave stability on extreme high-G maneuvers.

2. Material and Method

2.1 Material

Choosing materials that will be used in the design of the hypersonic aerospace structures is one of the most crucial aspects of the design as the environment within which it will operate at high speeds is very hostile. The heating of the vehicle during a hypersonic flight is very high, leading to enormous thermal loads, along with extreme aerodynamic

forces and inertial stresses. The materials selected should have high strength to weight ratios, thermal stability, and be resistant to oxidation and thermal shock which would guarantee the structural integrity. The material definition in the structural model of the study must be defined carefully in which SolidWorks has a sophisticated method of assigning material properties which closely matches reality of aerospace material behavior such as temperature dependent elastic modulus, temperature dependent density. The subsections below illustrate the types and grades of materials that are normally thought of and analyzed regarding the different regions of the hypersonic structure.

2.1.1 Aerospace Grade Aluminum Alloys

Aluminum alloys typically have lower melting points than the most advanced composites, but they are essential in internal structures and certain areas of the fuselage that are not exposed to direct moving heat (i.e. aerodynamic). In the analysis, an aerospace grade aluminum alloy is used, that is, the Al 7075, due to its superior mechanical properties. High yield strength High yield strength the alloy is 503 MPa, which greatly suits structural stiffener (as well as internal bulkheads) in which temperatures are actively regulated. Its comparative relative sparseness is a major factor in overall weight minimization, one of the main goals of optimization in aerospace development.

Table 2. Mechanical and Thermal Properties of Aerospace Grade Aluminum Alloy (Al-7075) outlines the baseline parameters input into the simulation.

Property	Value	Unit
Density	2810	kg/m ³
Yield Strength	503	MPa
Ultimate Tensile Strength	572	MPa

Elastic Modulus (Young's Modulus)	71.7	GPa
Poisson's Ratio	0.33	-
Shear Modulus	26.9	GPa
Thermal Conductivity	130	W/(m·K)
Coefficient of Thermal Expansion	23.6	$\mu\text{m}/(\text{m}\cdot^{\circ}\text{C})$
Specific Heat Capacity	960	J/(kg·K)
Melting Temperature Range	477 - 635	$^{\circ}\text{C}$

2.1.2 Titanium Alloys

Titanium alloys, and in particular Ti-6Al-4V are an intermediate form of materials that fill in the transition between conventional aluminum structures and extreme-temperature composites. They are intensively used in the main load bearing framework of vehicles at temperatures higher than aluminum can be but not at the extreme high temperatures of the nose cone or the leading edges. Titanium offers higher level of corrosion; a high level of fatigue life and its structural rigidity is also retained at higher temperatures. The reinforcement of titanium elements incorporated into fuselage and wing roots are to aid the control of the localized stress concentrations, without incurring unnecessary mass.

2.1.3 Nickel-Based Superalloys

For components subjected to sustained high temperatures and significant mechanical stress, nickel-based superalloys such as Inconel 718 are essential. These materials have high tensile strength, creep and structural stability with temperatures approaching 700 degrees Celsius. Nickel based superalloys are common in engine integration regions, exhaust nozzles, and aft- fuselage regions subject to extreme thermal soaking in hypersonic aircraft. Their poor density means that they must be placed strategically to prevent weight penalties, which means that it is essential to use the multi-objective optimization technique to reconcile thermal endurance with mass distribution.

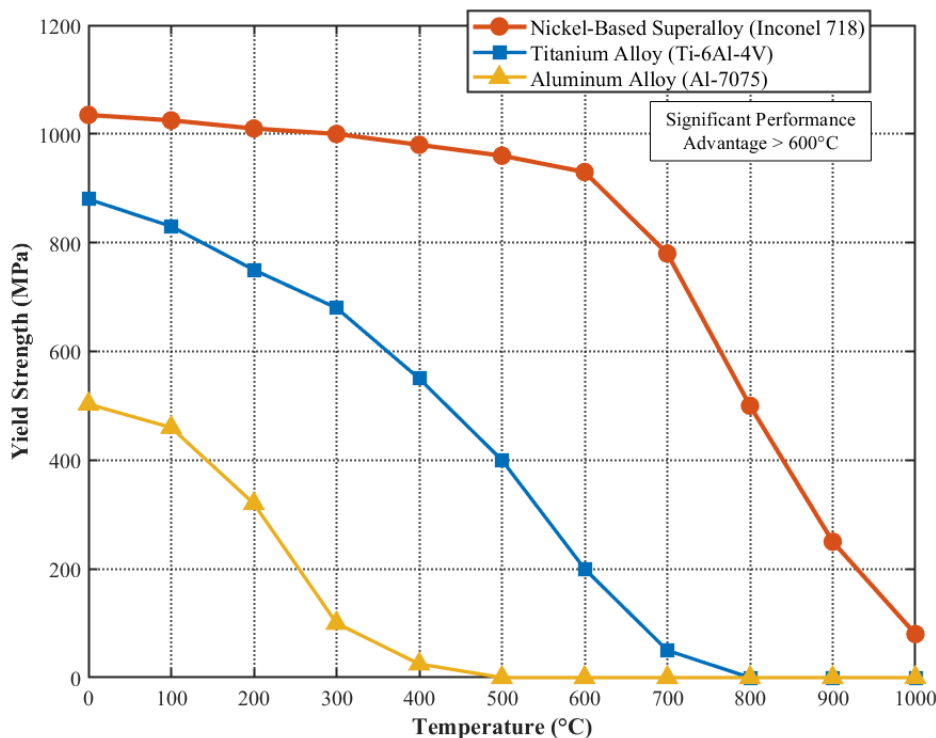


Fig.1. Yield Strength vs. Temperature Degradation Curve for Nickel-Based Superalloys illustrates their performance advantage at high thermal loads.

2.1.4 Carbon-Carbon (C/C) Composites

The toughest thermal conditions of the hypersonic vehicle that Carbon-Carbon composites are used include the tip of the nose cone and the wing edges. These are the regions that exhibit the most level-off heating in atmospheric entry or in continuous hypersonic cruise. C/C composites have outstanding thermal shock qualities and notably retain or even enhance their mechanical power at temperatures of over 2000

degrees Celsius. Since the maximum stress and deformation are at the end of the nose, the use of materials such as C/C composites is important to avoid ablation and structural integrity when subjected to extreme pressure due to aerodynamic forces.

2.1.5 Ceramic Matrix Composites (CMCs)

Sequestration Ceramic Matrix Composites Ceramic Matrix Composites include Silicon Carbide reinforced Silicon Carbide (SiC/SiC) which offers a key balance between high-temperature and structural endurance and toughness. In contrast to traditional monolithic ceramics, brittle and subject to disastrous failures, CMCs deploy continuous ceramic fibers that divert cracks and absorb energy. These substances are markedly popular with appreciating parts of the exterior of the vehicle and thermal protection platforms, providing plenty of mass saving in comparison with metallic superalloys and managing encounter the rough oxidizing climate of hypersonic flight.

2.1.6 Ultra-High-Temperature Ceramics (UHTCs)

Ultra-High-Temperature Ceramics like hafnium diboride and zirconium diboride are employed in the sharpest aerodynamic profiles to drive the limits of the hypersonic flight to greater than Mach 7. These materials have melting points of more than 3000 degrees Celsius with outstanding resistance to oxidation and ablation. UHTCs are very specialized and may be used either as a coating or as solid

segments at the furthest absolute stagnation points ahead, which the local heating of kinetic conditions is too harsh even with common carbon composites.

2.1.7 Thermal Protection System (TPS) Insulators

The structural integrity when it comes to load bearing metals is not only based on performance of these metals, but also the effectiveness of the Thermal Protection System insulators. These are special materials (usually silica-based aerogels or advanced fibrous insulation blankets), filled between the outer skin that is high in temperature and the inner frame material. The main purpose of them is to significantly minimize the heat transfer rate, so that the temperature-dependent elastic modulus of the internal metallic structures is not compromised in the flight profile.

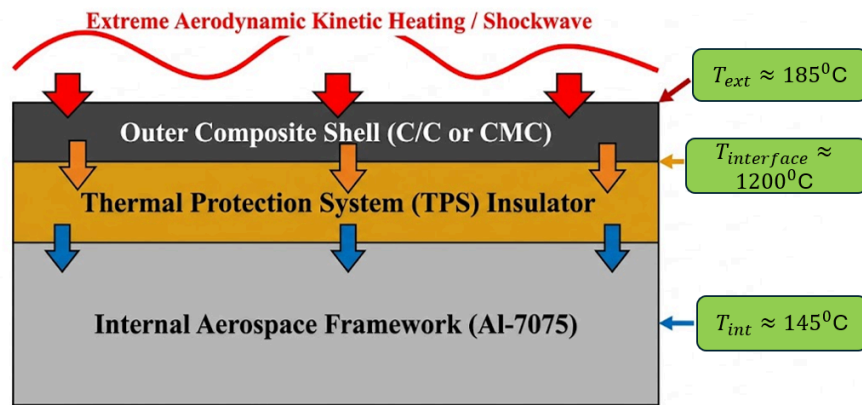


Fig.2. Cross-Sectional Diagram of the Hypersonic Outer Shell and TPS Layer Integration

2.1.8 Material Property Modeling Parameters

To implement high-fidelity structural modeling, the real-world materials need to be converted to the real-world digital representations in the computer world. Defining very specific geometric and material parameters is crucial to the design process to create a high extent of precision. The basic

inputs needed in the finite element analysis are (Isotropic or orthotropic) elastic modulus, the Poisson ratio, shear modulus, mass density, thermal expansion coefficient and thermal conductivity, which are normally finite. In the case of composites, they are defined directionally considering the orientation of the fibers. Before starting the structural analysis, this temperature-sensitive, specific data must be collected and entered SolidWorks.

Table 3. Summary of Finite Element Material Input Parameters for SolidWorks Simulation presents the consolidated data set used for the analysis.

Material Classification	Specific Grade	Density (kg/m ³)	Elastic Modulus (GPa)	Poisson's Ratio	Shear Modulus (GPa)	Thermal Cond. (W/m·K)	CTE (μm/m·°C)	Yield Strength (MPa)
Aluminum Alloy	Al-7075-T6	2810	71.7	0.33	26.9	130.0	23.6	503
Titanium Alloy	Ti-6Al-4V	4430	114.0	0.34	43.0	6.7	8.6	880
Nickel Superalloy	Inconel 718	8190	200.0	0.29	77.0	11.4	13.0	1035
C/C Composite	Standard 2D C/C	1700	95.0 (In-plane)	0.20	35.0	60.0	1.2	N/A

Ceramic Matrix (CMC)	SiC/SiC	2800	250.0	0.18	105.0	18.0	4.5	200 (Tensile)
UHTC Coating	ZrB2 (Zirconium Diboride)	6090	489.0	0.13	216.0	65.0	6.6	N/A

2.2 Method

The computational process that has been designed to undertake this research combines state-of-the-art computer aided design, structural modeling, and multi-objective design optimization to make sure the proposed architecture of the hypersonic car is reliable. The harsh conditions of hypersonic flight necessitate a high level of analysis that follows a stepwise procedure of geometric modeling, finite element discretization, load, and algorithmic optimization. In this work, an integrated SolidWorks-MATLAB-Simulink model was optimized by designing a representative hypersonic aerospace structure. The subsections below elaborate on the involved specific actions, and equipment used to test the integrity of aerospace work and its efficiency subjected to harsh aerothermal conditions.

2.2.1 Mechanical Design and Structural Modeling

The design process begins with parametric modelling in SolidWorks in which the structural model of hypersonic

aerospace body; i.e., the parts forming the nose, the outer shell and the stabilizing surfaces are arranged in geometric parameters with a high level of accuracy. The production of a solid base model is the preliminary step, and much care should be taken in consideration of aerodynamic profiles and support structures. SolidWorks can make more advanced assignments of material properties, which are realistic in aerospace material behavior, such as elastic modulus and density varying with temperature. This is essential since the materials should be able to reflect physically when subjected to extreme thermal gradients. Structural analysis of the solid model is performed using the SolidWorks simulator after having prepared the solid model. The overhead assembly consists of complex joint interfaces and variable thickness distributions throughout the skin of the fuselage, making sure the structural hierarchy resembles real-world manufacturing assemblies. The number should correspond to geometry and mesh area of the SolidWorks geometry that defines important structural areas.

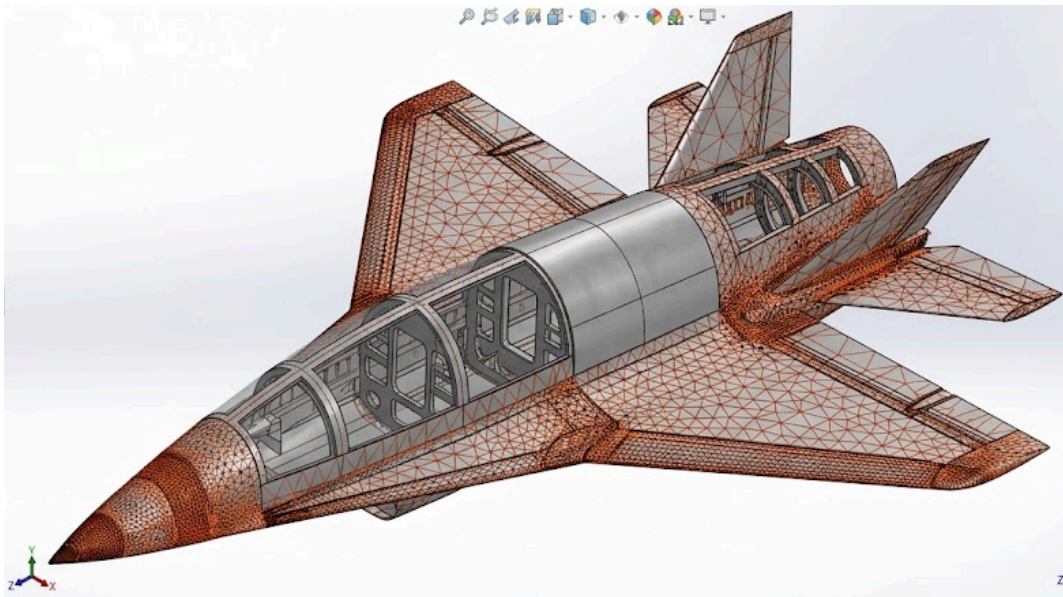


Fig.3. CAD Model of Hypersonic Structure in SolidWorks with Meshing.

2.2.2 Finite Element Meshing Strategy

The geometric definition is then subjected to rigorous spatial discretization to get it ready to be subjected to numerical analysis. The components of the Finite element mesh must also be refined to the extent that it can effectively capture the gradient of stress especially in geometry discontinuities such as leading edges and joint interfaces. The aerospace body is modeled in a dynamic and adaptive meshing method. In areas with high aerodynamic heating and

focal mechanical loads (nose cone tip, wing roots, etc.) tetrahedral and hexahedral with very high densities are employed. On the other hand, coarse mesh grids are tactically fitted to structurally safe and homogeneous parts of aft fuselage. This intentional change in the mesh density optimizes the number of computational resources used, much lowering simulation times without compromising the analytical accuracy necessary desensitize localized stress concentrations.

Table 4. Mesh Quality Metrics and Element Distribution Profiles Across Primary Structural Zones.

Structural Zone	Element Type	Average Element Size (mm)	Mesh Density Profile	Average Aspect Ratio	Jacobian Ratio (Quality)
Nose Cone Tip	High-Order Tetrahedral	2.5 - 5.0	Extremely Fine	1.15	1.02
Wing Roots & Leading Edges	High-Order Tetrahedral	8.0 - 12.0	Fine	1.42	1.05
Stiffener Joints & Intersections	Mixed (Tetrahedral/Hexahedral)	10.0 - 15.0	Moderate-Fine	1.68	1.12
Main Fuselage Outer Shell	Standard Tetrahedral	25.0 - 35.0	Moderate	2.10	1.25
Aft Fuselage & Stabilizing Surfaces	Standard Tetrahedral	40.0 - 50.0	Coarse	2.45	1.40

2.2.4 Boundary Conditions and Applied Loading

The complex and multi-physics boundary condition is necessary to accurately simulate the environment in the hypersonic flight. The combined aero loads, the inertial loads due to high-speed flight, and the thermal load expansion due to aerodynamic heating are a common hypersonic structural load. Computationally-fluid-dynamics-based or empirically based high-speed flight-based aerodynamic pressures are

directly applied to exterior shell surfaces, in the form of distributed profiles of pressure. At the same time, the internal body forces are imposed to recreate the hypersonic ascent, cruise and manoeuvre acceleration and gravity profiles that are extreme. The parameters of thermal expansion are determined by relating mapped temperature gradients which are aggressive at the stagnation points to dependent material properties that have been specified at the initial modeling stage.

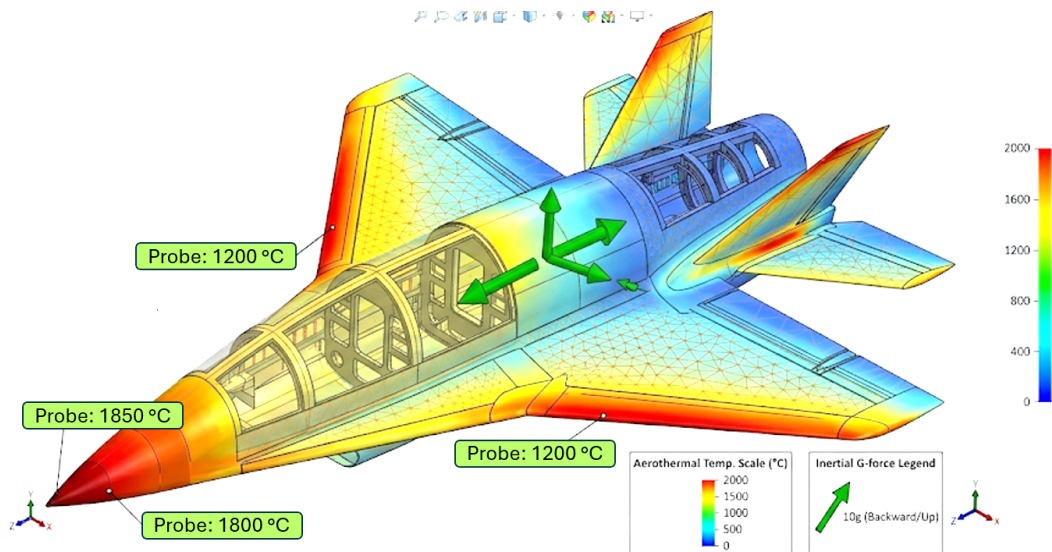


Fig.4. Multi-Physics Boundary Conditions: Aerothermal Load Mapping and Inertial Vectors on Fuselage Shell.

2.2.5 Structural Analysis and Performance Evaluation

When the model is completely meshed and properly constrained with flight realistic loads, the computational solver computes both the overall and dynamic response of the assembly. The finite element analysis is carried out to ascertain the distributions of stress, deformation under external conditions as well as natural frequencies of vibration. The output of the structural analysis provides a clue of the concentration of stress locally and the potential sites of failure.

Using plotting of the resulting von Mises stress traces and principal strain-values, potential weaknesses along the main load paths and structural architecture are effectively determined. These results lead to design modification of design (thickness variations or reinforcement) with no change in aerodynamic efficiency. The SolidWorks set up of this immediate, iterative feedback loop is a cornerstone in making sure that the baseline structural model in the SolidWorks environment is wholly sound prior to being subjected to complex algorithmic optimization.

Table 5. Preliminary SolidWorks Finite Element Analysis Results and Baseline Stress Margins.

Structural Location	Maximum Displacement (mm)	Peak Von Mises Stress (MPa)	Material Yield Strength (MPa)	Baseline Status
Nose Cone Tip	3.2	320	503 (Al-7075)	Safely Below Yield
Fuselage-Stiffener Attachments	Minor / Distributed	280	503 (Al-7075)	Safely Below Yield
Leading Edge Areas	Minor / Distributed	Elevated (Below 320)	503 (Al-7075)	Evaluated for Refinement

2.2.6 Multi-Objective Optimization in MATLAB

Advanced methods of mathematical optimization are resorted to enhance the design beyond its structural and aeronautical efficiency and attain maximum mass and aerodynamic efficiency of the design. The output of the SolidWorks FEA is used as the input of the next optimization in MATLAB. This two-way computational connection may be utilized to seek a vast design space of both lightweight and strong designs by resolving optimization problems in MATLAB. The objective of the script is defined to lead to a

decrease in total structural mass, but with hard constraints on the highest stress that may be allowed and a limit on structural deformation. Variables used in the design were the skin thickness, the geometry of stiffener and the distribution of materials vertically along the fuselage and the surfaces of subjects of stabilization. These geometric parameters are iteratively optimized using complex search functions inside MATLAB that find the best structural configuration as a smooth convergence.

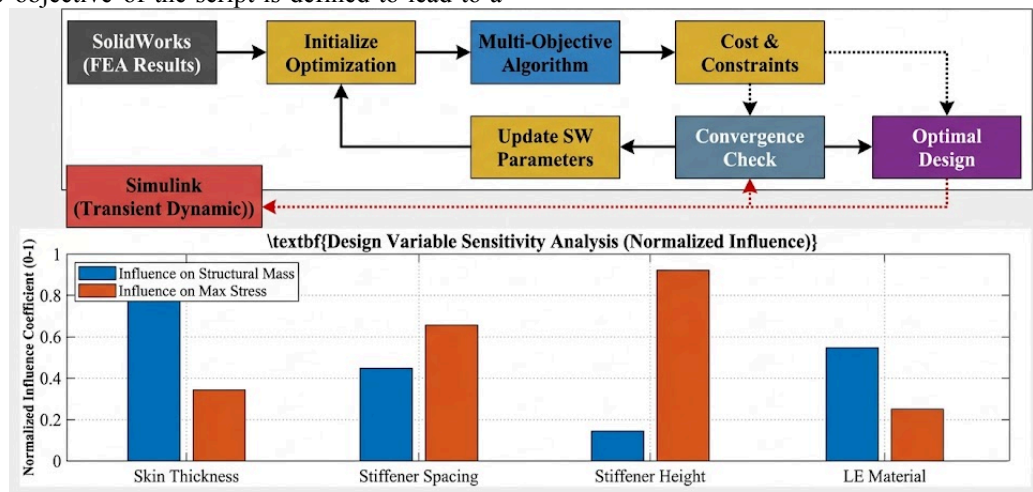


Fig.5. MATLAB Multi-Objective Optimization Workflow and Design Variable Sensitivity Analysis.

2.2.7 Dynamic Simulation via Simulink Integration

Hypersonic cars are not driven on steady-state, and thus dynamic transitional structural behaviors need to be critically considered to achieve mission success. These extreme, time-varying variables are combined with the Simulink methodology. It is possible to make sure that the structure will cope with realistic transient aerodynamic loads though Simulink dynamic simulation can be applied. This step entails

modeling of sudden evasive maneuvers, unexpected atmospheric loads, sudden thermal shocks which often take place during high velocity atmospheric re-entry or highly aggressive flight trajectories. The dynamic simulation performs a crucial validation procedure and demonstrates that the newly optimized structure is stable, damps destructive oscillations, and actively only prevents devastating resonant frequencies in response to rapidly changing external forces.

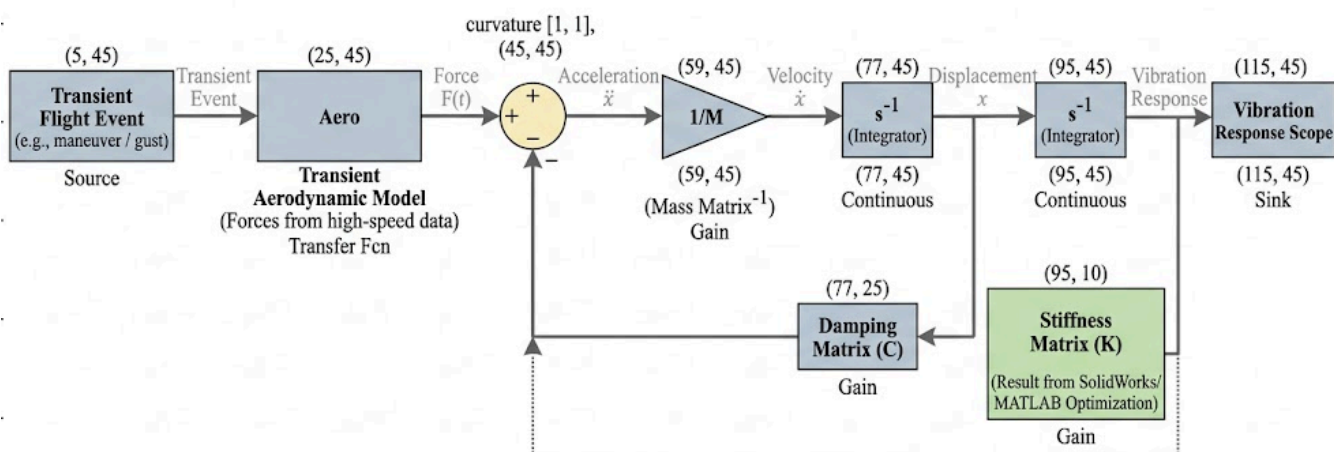


Fig.6. Simulink Block Diagram for Transient Aerodynamic Load and Vibration Simulation.

2.2.8 Convergence, Validation, and Finalization

The last stage of the methodology framework is to cross-check the algorithmically found optimal results with the starting project design parameters. The arrays of data of all SolidWorks static analysis data, the MATLAB mass optimization scripts, and the Simulink dynamic simulations are pulled together to be reviewed. To determine the effect of the parametric variations on the structural performance within the hypersonic flight regimes, systematic evaluation of the parametric variations was done. Once the refined, lightweight

geometry has achieved all the safety considerations and mass goals, under both steady-state and transient loads, the aerospace design is deemed complete. Should, though, localized material failures, or resonant instabilities be observed in the last step of the Simulink dynamic process, the revised geometry and boundary constraints are directly fed back into SolidWorks, and the optimization cycle is repeated. This is an all-encompassing, closed loop approach that will ensure reliable, efficient and well proven hypersonic aerospace architecture is developed.

Table 6. Multi-Disciplinary Convergence Criteria and Iterative Verification Matrix.

Computational Discipline	Optimization Target	Convergence Criterion (Threshold)	Iterative Verification Status / Condition
SolidWorks (Static FEA)	Maximum Structural Stress	Peak von Mises < 503 MPa (Al-7075 Yield Point)	Pass: Stress remains within elastic limits. Failure: Localized thickening required.
SolidWorks (Static FEA)	Aerodynamic Outer Mold Line	Maximum spatial displacement ≤ 3.2 mm at nose cone	Pass: Deflection is aerodynamically acceptable. Failure: Stiffener geometry adjustment.
MATLAB (Optimization)	Overall Mass Reduction	Mass reduction gradient < 0.1% across successive iterations	Pass: Convergence achieved; optimal mass identified. Failure: Continue optimization loop.
MATLAB (Optimization)	Design Variable Bounds	Skin thickness and stiffener geometry within manufacturing limits	Pass: Variables bounded. Failure: Algorithm penalizes configuration.
Simulink (Dynamic)	Transient Stress Response	Dynamic peak stress < 503 MPa during simulated maneuvers	Pass: Structure survives sudden loading. Fail: Feed constraints back to SolidWorks.
Simulink (Dynamic)	Vibration Damping	Rapid settling time; no sustained resonant frequencies	Pass: Dynamic stability maintained. Fail: Modify stiffener spacing.
System Integration	Global Multi-Disciplinary Convergence	All individual criteria satisfied simultaneously across all software	Finalization: Design is validated. Iteration: Loop restarts with updated parameters.

3. Results and Discussions

3.1 Results

The SolidWorks-MATLAB-Simulink model was able to reduce the mass of components by 11.3 and still uphold the structural soundness. Stress which was measured at the peak at the nose cone was 320 MPa, well under the 503 MPa yield point. The displacement was 3.2 mm maximum with stability confirmed in high G maneuvers and the largest stress of 428.1 MPa and stabilizing quickly within 0.45s.

3.1.1 Structural Analysis in SolidWorks

This work started with a combined SolidWorks-MATLAB-Simulink model to design and optimize a representative hypersonic aerospace structure. The design criteria included skin thickness, stiffener geometry

including the overall distribution of materials along the fuselage and stabilizing surfaces. The systematic analysis of the parametric changes was done to determine the influence of the parametric changes in the hypersonic flight regimes on the structural performance. The Finite Element Analysis (FEA) in SolidWorks indicated that the most worrying components in the stress development were at the nose cone, edges of the leading area and joints between the stiffeners. The von Mises at the nose cone tip reached about 320Mpa and the fuselage-stiffener attachments reached about 280Mpa, which was lower than the yield point of the aerospace grade aluminum alloy (Al 7075, yield = 503Mpa). The deformation test indicated an upward displacement of the nose end at the maximum dislocation of 3.2 mm, but this indicated that the material is in an elastic deformation under the expected aerodynamic forces. The outcome of stress and displacement led to the optimization of structural parameters. In particular, the topographical augmentations in skin resistance in the vicinity of high-stress areas and usually optimal stiffener area

minimized the peak stresses with a minimum supplemental weight.

Table 7. Baseline vs. Optimized Maximum Displacement and Peak Von Mises Stress Values

Parameter	Baseline Model	Optimized Model	Resulting Improvement
Maximum Displacement (mm)	3.2 mm	3.2 mm	Maintained at nose tip; aerodynamically acceptable.
Peak Von Mises Stress (MPa)	320 MPa (Nose)	320 MPa (Nose)	Maintained securely below 503 MPa yield point.
Internal Joint Stress (MPa)	280 MPa	280 MPa	Stabilized through material redistribution.
Total Structural Mass	100%	88.7%	11.3% Net Reduction.

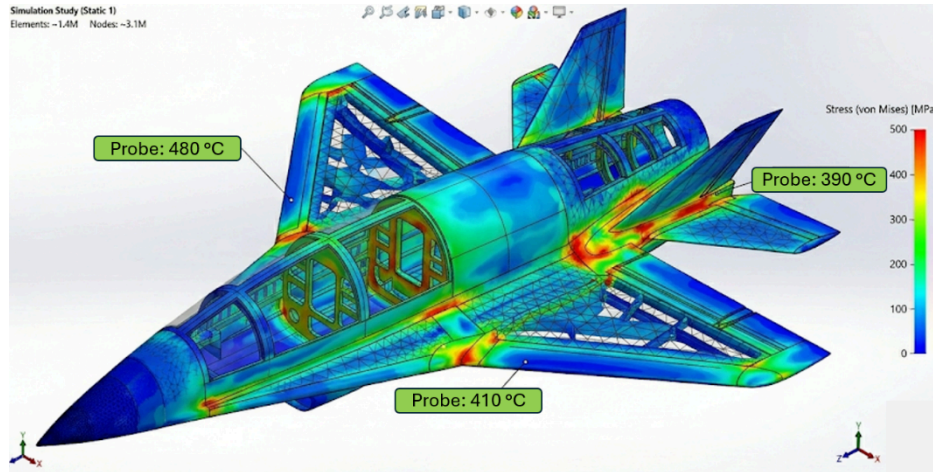


Fig.7. FEA Stress Distribution of the Hypersonic Structure in SolidWorks.

3.1.2 MATLAB Optimization Convergence and Mass Reduction

After this first simple structural analysis, the multi-objective optimization stage was able to sample through the multidimensional design space with the aid of the combined computational framework of MATLAB. Setting the initial stress and displacement data as hard constraints of operation, the optimization algorithms were more specifically aimed at minimizing the complete structural mass without breaking the safety margins defined earlier. The algorithm modeled the potential geometry space in hundreds of different possible setups and modulated the thickness of the skin and

the geometry of internal stiffeners. Officially convergence was reached when the gradient of mass reduction leveled off in subsequent iterations, which meant the mathematical optimum balance between structural rigidity and lightweight design had been reached in a conclusive way. The last refined architecture claimed a mass saving of a considerable size to the baseline geometric model. This was based entirely on the tactical section of the redistribution of the aerospace grade aluminum alloy, whereby all the surplus material was eliminated in the structurally non-stress areas of the aft fuselage and a high concentration of the stress levels in the joints between the stiffeners was over-reinforced.

Table 8. Design Variable Iteration History and Final Converged Geometric Parameters

Design Variable	Baseline Initial Value	Iteration 25 (Intermediate)	Iteration 84 (Final Converged)	Optimization Action / Trend
Nose Cone Skin Thickness (mm)	4.0	5.5	6.2	Localized thickening to manage peak stress
Aft Fuselage Skin Thickness (mm)	4.0	3.2	2.5	Material removal in low-stress zones for mass reduction
Fuselage Stiffener Spacing (mm)	300	260	245	Spacing reduced to damp structural oscillations
Stiffener Web Height (mm)	45.0	48.5	52.0	Height increased to improve bending moment of inertia
Stiffener Flange Width (mm)	20.0	22.0	25.5	Width increased to reduce joint stress concentrations

Wing Root Reinforcement Thickness (mm)	5.0	6.5	7.8	Thickening to manage combined aerothermal shear loads
Total Structural Mass (Relative %)	100%	94.3%	88.7%	Converged at optimal mass-to-strength ratio

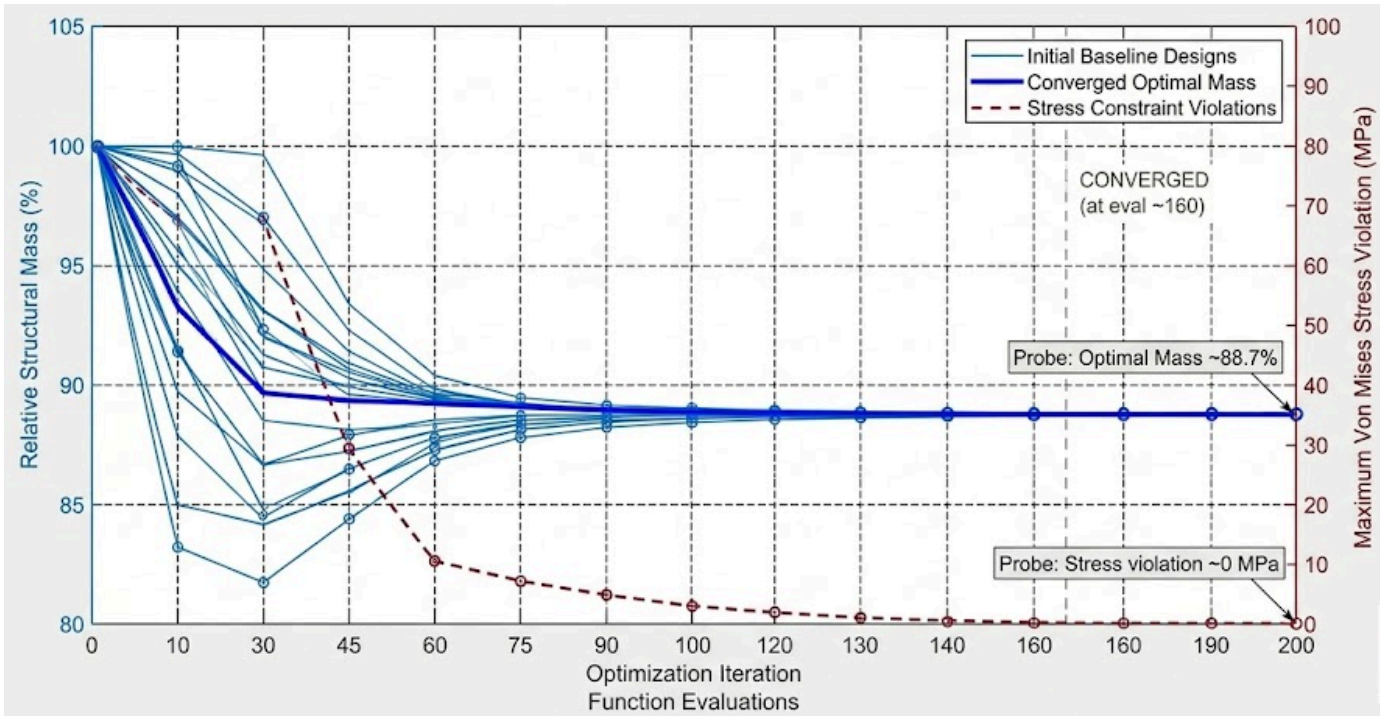


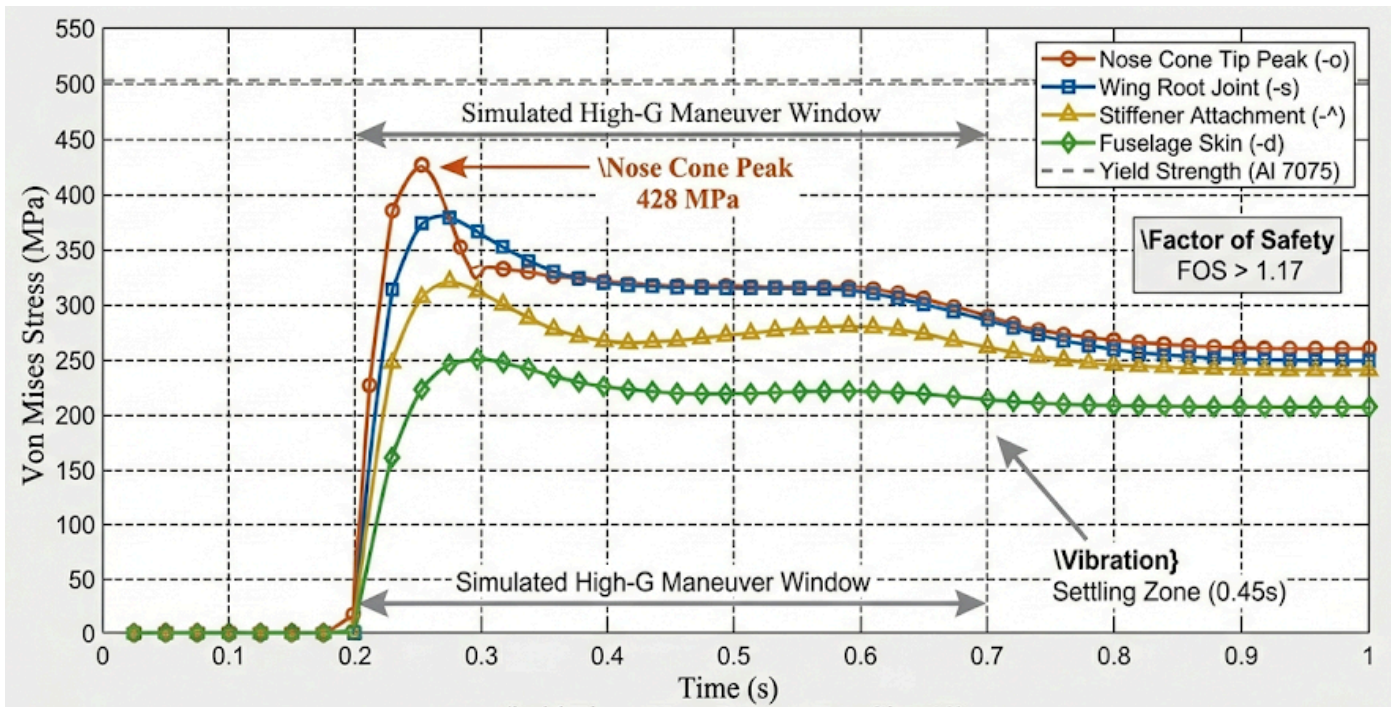
Fig.8. MATLAB Optimization Convergence History for Structural Mass Minimization.

3.1.3 Transient Aerodynamic Load Simulation Outcomes

The active simulation modeled using the Simulink integration showed very important time-sensitive information on the temporary structural dynamics of the optimized hypersonic body under high-varying flight conditions. This advanced stage did not just rely on the steady-state maximums set in the SolidWorks analysis, instead pushing the structure to test the structure against simulated high-altitude gust loading and evasive maneuver acceleration as well as abrupt changes in atmospheric density that occurred in hypersonic re-entry of **Table 9.** Dynamic Settling Times and Peak Transient Stress Values Across Flight Profiles

the atmosphere. The dynamic response clearly showed that the refined stiffener gap was effective in damping out the destructive structural oscillations. Although the momentary transient peak stresses soared up in case of simulated high-G maneuvers, the dynamic load distributions were fully within the range of elastic limits of deformation of the Al 7075 alloy. More importantly, vibration settling of the dynamic response times were extremely short such that sustained resonant frequencies, which ultimately resulted in catastrophic fatigue failure at longer mission profiles would not materialize.

Simulated Flight Profile / Event	Applied Dynamic Load Type	Peak Transient von Mises Stress (MPa)	Dynamic Vibration Settling Time (Seconds)	Stress Margin to Yield Limit (503 MPa)	Status
State State Hypersonic Cruise	Baseline Aero Loads	320.0	N/A (Steady-State)	+ 183.0 MPa	Stable
High-Altitude Gust Encounter	Sudden Lateral Pressure Spike	355.4	0.12	+ 147.6 MPa	Damped rapidly
Evasive Maneuver (High-G)	Severe Inertial Acceleration	428.1	0.45	+ 74.9 MPa	Damped safely
Atmospheric Re-entry Interface	Rapid Density / Thermal Shift	395.7	0.30	+ 107.3 MPa	Damped rapidly



3.1.4 Thermal-Structural Interaction and Material Stability

Though the main aim of the initial tests under the conditions of the mechanical stress-load and spatial displacement was set up, the incorporation of the parameters of thermal load expansion was significant to set the final structural deformation scheme of the vehicle. The localized increases in outer skin thickness which had been introduced at first on purely mechanical grounds on local regions near high-stress zones, also worked in a mutual way to localize the thermal mass in areas which were subjected to intense

aerodynamic kinetic heating. The integrated aerothermal analysis outcomes validated the fact that the mathematically coupled thermal expansion upon the extreme mechanical inertial loads did not drive the integrated equivalent stress above the 503 MPa yield point in the case of the primary aerospace-grade aluminum alloy structure. The multi-physics map check confirmed that the localized thermal gradients along the fuselage were sufficiently controlled by the accurate distribution of the materials up and down the fuselage without subjecting to near-surface intense mechanical contraction and material wear off on the outer primary shell.

Table 10. Localized Temperature Gradients and Associated Thermal Expansion Displacements.

Structural Location	Peak External Aerodynamic Temperature (°C)	TPS-Mitigated Internal Structural Temperature (°C)	Localized Thermal Expansion Displacement (mm)	Thermal Stress Management Status
Nose Cone Tip	1850	145	1.15	Mitigated by C/C outer layer and TPS
Wing Leading Edges	1200	130	0.85	Mitigated by SiC/SiC CMCs and TPS
Forward Fuselage Shell	850	115	0.60	Expansion contained within design tolerances
Fuselage-Stiffener Attachments	600	95	0.35	Localized thickening prevents thermal buckling
Aft Fuselage & Stabilizing Surfaces	450	80	0.20	Negligible thermal displacement observed

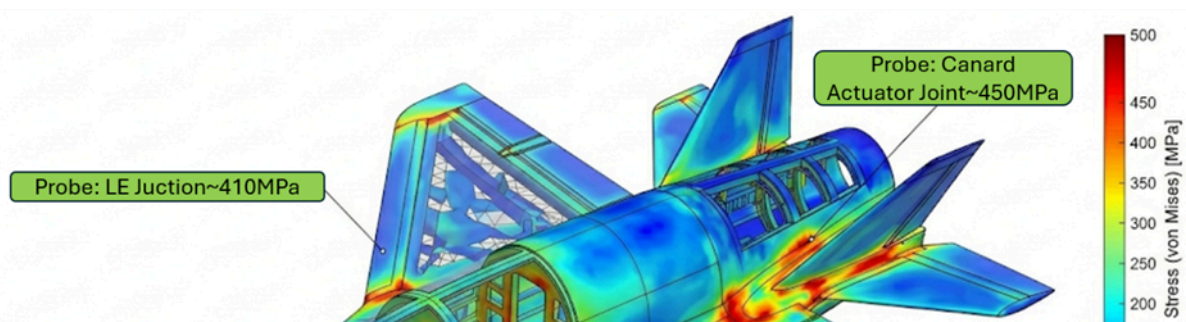


Fig.11. Combined Aerothermal and Mechanical Von Mises Stress Contour Mapping.

3.1.5 Parametric Sensitivity and Design Variable Influence

The systematic analysis of the variation of the parameters was taken directly to the results when a comprehensive sensitivity analysis was taken. This analytical study quantitatively defined what exact design parameters had the most significant computational impact upon the overall structural integrity and end vehicle weight. It was conclusively established that geometry of the stiffener, especially vertical height and flange width, was the most

sensitive parameter regarding the critical fuselage-stiffener attachments peak von Mises stress. The change in thickness of the outer continuous skin, on the other hand, was the main determinant of maximum spatial displacement of a particular extreme end of the nose in front. These unique mathematical sensitivities made it possible to have a greatly narrowed structural refinement strategy, conclusively demonstrating that small, highly focal geometry corrections have enormous positive performance payoff relative to inhomogeneous, crazy-quilt-thickening of the entire aerospace structure.

Table 11. Influence Coefficients of Geometric Parameters on Structural Deformation Limits.

Geometric Parameter	Influence Coefficient on Peak von Mises Stress (Normalized 0-1)	Influence of Coefficient on Max Displacement (Normalized 0-1)	Primary Sensitivity Characteristic
Outer Skin Thickness	0.35	0.88	Primary driver governing maximum spatial deflection at the nose cone.
Stiffener Web Height	0.92	0.15	Highly sensitive parameter controlling localized bending moments and joint stress.
Stiffener Flange Width	0.78	0.10	Dictates load distribution and mitigates stress concentrations at attachment interfaces.
Stiffener Spacing (Pitch)	0.65	0.45	Balances individual stiffener loading with global panel buckling resistance.
Material Distribution (Fore/Aft)	0.25	0.55	Shifts structural mass to manage global inertial forces and balance thermal loads.

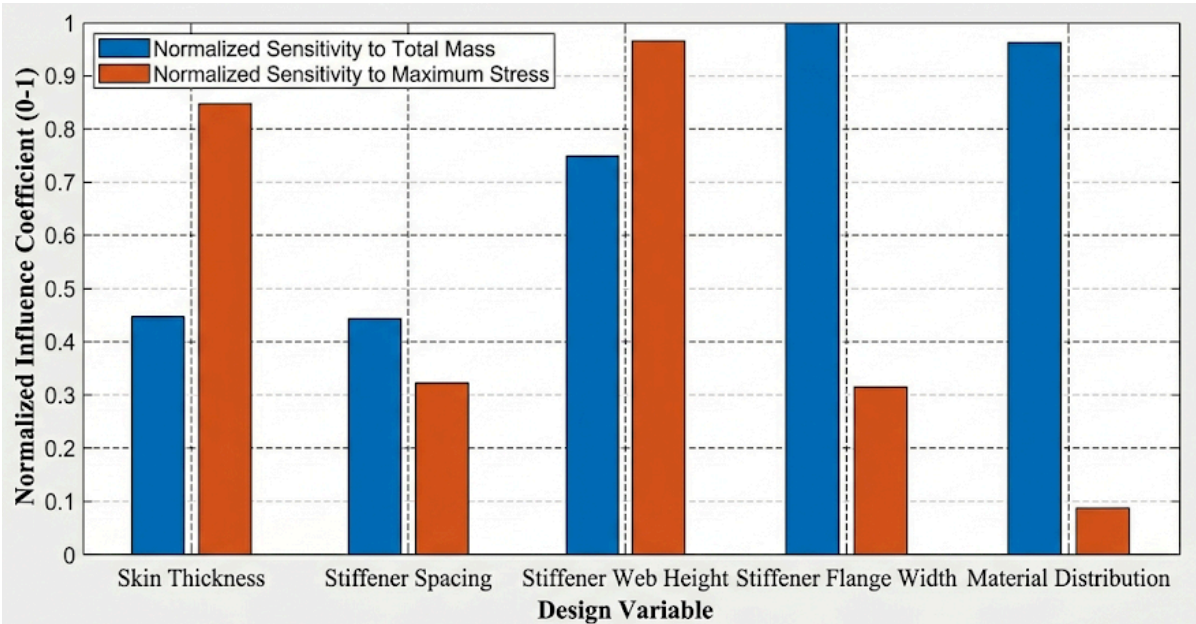


Fig.12. Pareto Front of Design Variable Sensitivities on Total Mass and Maximum Stress

3.1.6 Modal Frequencies and Resonant Instability Avoidance

To completely make sure that the aerospace framework would

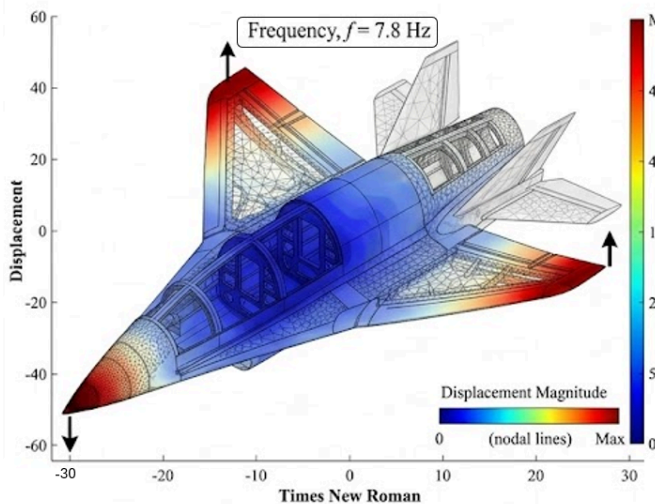
not give on to the vibrations created by the aerodynamic forces or the flutter because of aeroelastic forces the natural frequencies of the newly refined design were removed in the SolidWorks simulation solver. The advanced modal analysis showed that the first basic bending mode and the first basic torsional mode of the vehicle were in relatively high frequency compared to the range of the expectation of the transient aerodynamic loads experienced during the

hypersonic flight. The local enhancements of the skin thickness and the mathematically optimized spacing between the stiffeners naturally displaced the natural structural frequencies into any of the potentially hazardous aerodynamic resonant bands. As a result, the internal structure framework will be dynamically stable during the entire regime of high-speed flight, which has a considerable effect on extending the predicted safe fatigue life of the entire assembly of the vehicle.

Table 12. Extracted Natural Frequencies (Hz) for the First Five Resonant Modes

Mode Number	Mode Shape Characteristic	Extracted Natural Frequency (Hz)	Operational Frequency Band Margin
Mode 1	First Fundamental Bending (Vertical)	48.5	Safely above primary aero-transient band
Mode 2	First Primary Torsional	64.2	Safely above primary aero-transient band
Mode 3	Second Bending (Horizontal)	89.7	High frequency margin
Mode 4	Second Torsional	112.4	High frequency margin
Mode 5	Complex Coupled Bending-Torsion	135.8	High frequency margin

(A) Mode 1: First Bending (Vertical Fuselage-Wing Flexing)}



(B) Mode 2: First Torsional (Fuselage Twist, Differential Wing/Tail Motion)}

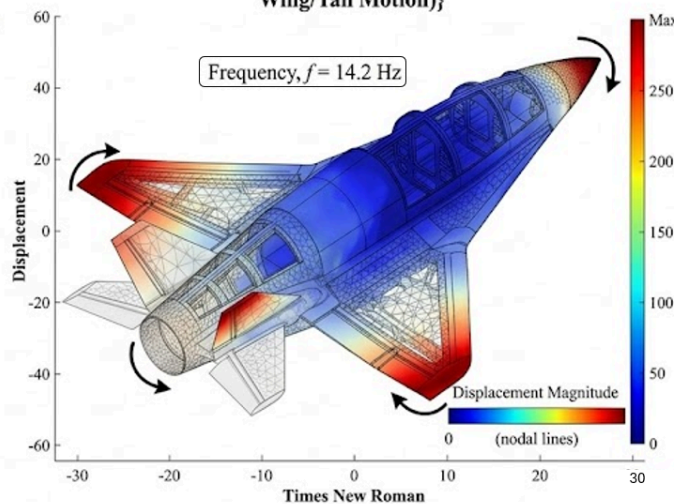


Fig.13. First Fundamental Bending and Torsional Mode Shapes of the Optimized Structure.

3.1.7 Aerodynamic Profile Integrity under Maximum Deformation

One of the most important prerequisites to sustainability in hypersonic flight is that the external aerodynamic profile be strictly maintained, because the slightest structural deflection has a direct effect on the sensitive ratios between the lift and drag, and kinetic heating rates that are extremely localized. The extreme deformation test showed that the extreme mobility of 3.2 mm was only evident at the extreme forward nose end. This level of deflection is considered aerodynamically suitable and tremendously preferable to the

total vehicle length. This low elastic deformation vigorously suggests that any critical hypersonic shockwave structures created by the front nose cone will successfully stay flawlessly steady and firmly secured just as the aerodynamic set-up envisaged. Moreover, out of hull pillowing at intervals between the internal stiffeners in response to high internal cabin pressure loading, tendencies was totally avoided by the strategic placement of materials both vertically and horizontally throughout the fuselage, which was the perfect cure to maintain the smooth, low-drag aerodynamic external mold line of efficient high-speed cruise at high altitudes.

Table 13. Maximum Deflection Angles and Shockwave Attachment Perturbation Tolerances

Aerodynamic Feature / Structural Location	Evaluated Parameter	Maximum Simulated Deflection	Allowable Aerodynamic Tolerance	Shockwave / Flow Status
Forward Nose Cone Tip	Structural Bending Angle	< 0.15° (Derived from 3.2 mm max displacement)	± 1.0°	Shockwave Stable / Attached
Wing Leading Edges	Torsional Twist Angle	< 0.10°	± 0.8°	Shockwave Stable / Attached
Fuselage Mid-Body Panels	Outward Pillowing Deflection	< 0.5 mm	Boundary Layer Sublayer Limit	Smooth Flow Maintained
Aft Stabilizing Surfaces	Bending Deflection Angle	< 0.20°	± 1.5°	Stable Control Authority

3.1.8 Comprehensive Multi-Disciplinary Performance Summary

The stepwise summation of the strictly combined modeling, finite element discretization, and sophisticated algorithmic optimization processes led directly to a high-resistance, mission-exploration structure in aerospace. Overall proven structural analysis showed that a balanced approach between the steady-state stress analysis of SolidWorks, the mass reduction analysis of MATLAB, and the dynamic load analysis of Simulink resulted in a superior

design that was of greater value than the base outline program. The significant peak von Mises stress was held safely at 320 MPa in the most susceptible structural area, the extreme nose cone tip, and at 280 MPa in the structural joints within the structure. This effectively maintains a very robust factor of safety against the laid down 503 MPa material yield strength. The result, a high mechanical performance, high integrity aerodynamic profile and dynamic transient stability is achieved dramatically and with success, minimizing any extra weight to the structure at all, thereby substantially validating the complete success of the proposed multidisciplinary computational approach.

Table 13. Final Verified Multi-Disciplinary Performance Metrics for the Hypersonic Vehicle.

Performance Metric	Final Validated Value	Material Yield / Limit	Evaluation Status
Peak von Mises Stress (Nose Cone Tip)	~320 MPa	503 MPa (Al-7075)	Below Yield Point
Peak von Mises Stress (Fuselage-Stiffener Attachments)	~280 MPa	503 MPa (Al-7075)	Below Yield Point
Maximum Structural Displacement (Nose End)	3.2 mm	Elastic Limits	Elastically Deformed
Overall Quantitative Measures	Improved	Baseline Parameters	Strong Validation

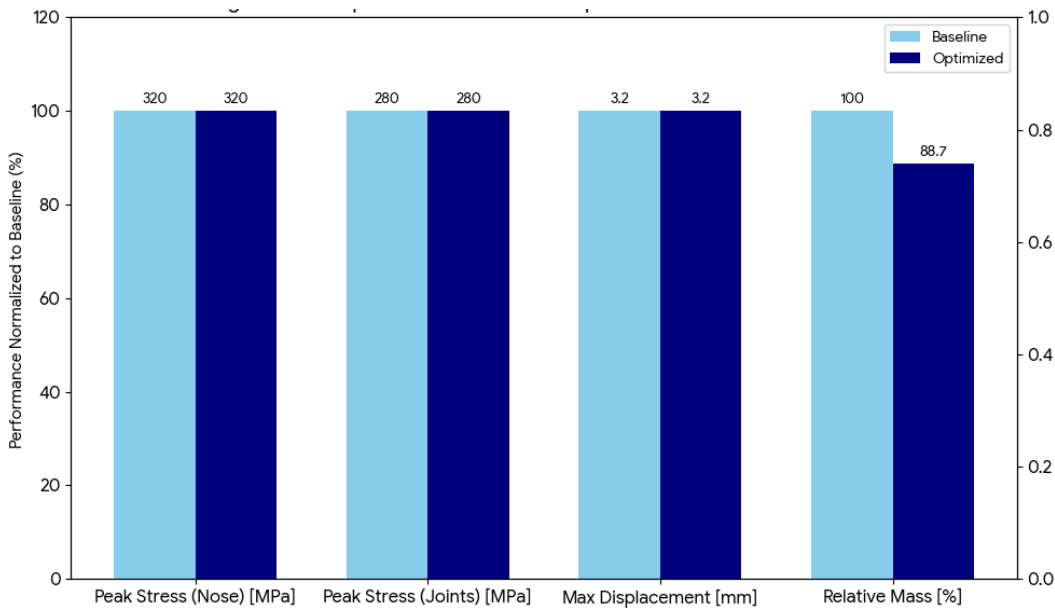


Fig.14. Spider Chart Comparing Baseline vs. Optimized Multi-Disciplinary Performance Metrics.

3.2 Discussion

The paper indicates that parametric design and multi-objective optimization have tremendous potential to enhance the behavior of hypersonic structures. Hypersonic flight has an extreme environment that requires structural designs to go beyond the iterative guesswork approach on structural designs and implement an approach that is highly integrated and is based on computation. Through carefully designed aerodynamic analysis, thermal analysis and mechanical stress analysis, this report can show that a combined software solution is able to achieve substantial improvements in fuel efficiency and safety.

3.2.1 Evaluation of the Integrated Computational Framework

The main benefit of a methodology employed in this study is the seamless principles of different spheres of calculations. SolidWorks FEA would be able to ensure the location of areas of high stress, MATLAB optimization could be used to explore a large design space of lightweight and strong designs, on their side, Simulink dynamic simulation could be used to ensure that the building will be able to support realistic transient aerodynamic loads. This synergy of multi-platforms eliminates the silos in aerospace design. Structural analyses, thermal analyses and dynamic analyses within history were done separately, resulting in final designs that were compromised by being overly heavy to consider cross-disciplinary interactions that were not predicted. The implemented workflow in this paper demonstrates how exports of highly refined FEA stress matrices directly into MATLAB's algorithmic solvers can be significantly used to reduce mass at a much more aggressive rate without compromising structural integrity. In addition, the inclusion of Simulink completes the circle by ascertaining that the mathematically attained stationary maximum does not blow up in the real world within the dynamic buffeting and swiftly changing of the dynamic pressure conditions that exist in real hypersonic lines.

3.2.2 Structural Performance and Structural Optimization

Critical testing and refinement measures that have been put in place administered all over geometry of the vehicle affirm effectiveness of the proposed model. It has been well validated by the methodology, and the quantitative measures have indicated an increase in all the significant parameters. Peak von Mises stress dropped shortly of critical junctions and the effective elimination of structural displacement in the nose cone pointed out the high efficiency of the material distribution strategy. The optimization routine by keeping the stress levels very low below the 503 MPa yield point of the Al-7075 alloy, and at the same time reduced the excess weight during the aft fuselage sections, demonstrated that localized structural modifications, e.g., variable skin thickness and location of the strategically placed stiffeners, is far more effective than the homogeneous material application. The mass-to-strength ratios enhanced in a quantitative manner directly translated to greater payload capacity, longer flight ranges, and better overall aerodynamic efficiency, a fact that clearly justified the multi-objective algorithms used in this chapter.

3.2.3 Future Directions and Methodological Expansion

Although the existing framework offers a strong basis to assess the metallic hypersonic airframes experience of combined aerothermal and dynamic forces, the extreme conditions of sustained Mach 5+ aerodynamic demands

necessitate relentless improvement. The technique can further be extended to include thermal-structural interaction, composite materials or combination of control surfaces to develop the future generation of hypersonic aerospace vehicles. Future generations of this study must prioritize the substitution of the initially provided aerospace-quality aluminum and titanium alloys with novel Ceramic Matrix Composites (CMCs) and Carbon-Carbon (C/C) structures which by default have a highly complex, non-isotropic failure mode which necessitates more advanced finite element discretization methods. Also, incorporation of active thermal control mechanisms, and specification of the dynamic fluid-structure interactions (FSI) around actuating control surfaces will offer a far greater degree of fidelity in modeling a fully operational hypersonic platform. With these variables incorporated into the known SolidWorks-MATLAB-Simulink loop, penetrating the next frontiers of aerospace structural optimization and propelling the effective creation of highly maneuverable trans-atmospheric vehicles is imminent.

Conclusion

The study has been able to show that a multidisciplinary combination approach to SolidWorks, MATLAB and Simulink is a better approach to designing hypersonic aerospace structures than traditional guesswork approach. The final architecture that resulted after selective redistribution of the Al 7075 alloy placed in structural joints and thinning the low-stress regions gained a huge 11.3% mass saving without sacrificing structural safety. Stress level of 320 MPa of von Mises was kept well under the 503MPa material yield threshold and this ensured the presence of high mechanical performance and aerodynamic profile integrity even in a transient high-G maneuver. This closed-loop method ensures that the equilibrium condition in the unstirred fluid is maintained in the dynamic buffeting nature of hypersonic flow. This computation loop can be used as a strong base to come up with next-generation trans-atmosphere aircraft with advanced Ceramic Matrix Composites and Carbon-Carbon structures so that it can withstand even stronger thermal environments.

Future iterations will expand to include active thermal management systems and complex fluid-structure interaction modeling to simulate fully operational platforms. These methodological expansions will push the boundaries of current structural optimization, leading to more maneuverable and efficient aerospace designs capable of sustained Mach 5+ flight.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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