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Structural Analysis on Unconventional Section of Air-Breathing Cruise Vehicle

BASHETTY SRIKANTH[1], K.DURGA RAO[2], Dr.S.SRINIVAS PRASAD[3]

[1]PG Scholar, MLR Institute of Technology, Hyderabad-500 043, India.
(Corresponding author, Email: srikanth.aeforu@gmail.com, 9052361566)

[2]Associate Professor, Department of Aeronautical Engineering, Malla Reddy College of Engineering &Technology, Hyderabad-500 017, India. (Email: durgaraok9@gmail.com)
[3]Professor, Department of Aeronautical Engineering, MLR Institute of Technology, Hyderabad-500 043, India.
(Email:sanakaprasad@yahoo.com)

Abstract - High temperatures encountered during hypersonic flight lead to high thermal stresses and a significant reduction in material strength and stiffness of airframe of air-breathing hypersonic cruise vehicle. Thermo-structural analysis on hypersonic vehicle airframe is one of the challenging problems since the properties, yield strength and ultimate tensile strength varies with temperature. Thermal analysis, structural analysis and coupled thermo-structural analysis has been carried out on an unconventional section of hypersonic air-breathing cruise vehicle subjected to high temperatures and flight loads. The unconventional section having constant cross section designed for housing the fuel tank and intake-cowl opening mechanism of cruise vehicle has been modeled using commercial software CATIA V5. Analytical stresses have been calculated due to flight loads at control surface deflection of 0° and 15° at Mach 6, 590°C temperature. Linear relation between E, G and K with temperatures has been considered in the computational and analytical calculations. Computational analysis has been carried out using commercial software ANSYS Workbench in the present study. Static analysis has been carried out on section subjected to maximum bending moment of 6900 N-m to verify the structural integrity of the section. The results obtained from computational analysis are in good agreement with analytical results. This study provides the material combination which ensures structural safety of airframe of cruise vehicle at all operating conditions.

Keywords: Hypersonic cruise vehicle, Airframe, Temperature, Flight loads, Thermal analysis, Structural analysis, Yield strength, Ultimate tensile strength.

1. INTRODUCTION

The perceived advantages of hypersonic technology for space and missile applications have made many countries to initiate ambitious programs in recent times. At present many advanced countries are pursuing the development of hypersonic cruising vehicles. India is the second country to have planned an autonomous flight of the hypersonic air-breathing vehicle, the first being the USA which demonstrated the flights through X-43 and X-51 programs. The main objective in every airborne vehicle is to have a structure which can withstand various loads (i.e. both ground and air loads) in the lowest possible weight so that it functions effectively and efficiently. For these reason, the aerospace field has become evolutionary in almost every field of technology including thermal, propulsion, structural, metallurgical, aerodynamics, etc. The need to have the best possible configuration both aerodynamically and structurally with the best suitable material along with the desired speed factor, efficiency, etc. has led to many innovations in terms of materials, structural, aerodynamic configurations and propulsion efficiency etc.

2. OBJECTIVE OF THE PROJECT

To discretize the airframe of hypersonic air-breathing cruise vehicle into six sections and consider an unconventional section having uniform cross section, designed for housing the fuel tank and intake-cowl opening mechanism of hypersonic air-breathing cruise vehicle for the analysis. To calculate analytical stresses due to flight loads at control surface deflection of 0° and 15° at Mach 6, 590°C temperature. To carry out computational analysis for finding the deformation and stresses over the airframe of hypersonic cruise vehicle with Al alloy and Ti alloy material combination subjected to flight loads and high temperatures. To prove the material combination of Al alloy considered for Bulkheads, top panel, side panels and Ti alloy considered for bottom panel with suitable thermal protection system ensures structural safety of airframe of cruise vehicle at all operating conditions.

3. PROBLEM STATEMENT

The airframe of hypersonic air-breathing cruise vehicle has been discretized into six sections as shown in figure 1. An unconventional section P4 having uniform cross section designed for housing the fuel tank and intake-cowl opening mechanism of hypersonic air-breathing cruise vehicle is considered for the analysis. The length of the cruise vehicle has been conceptualized as 5.6m. The maximum width and height of the cruise vehicle is 0.8m and 0.4m respectively.

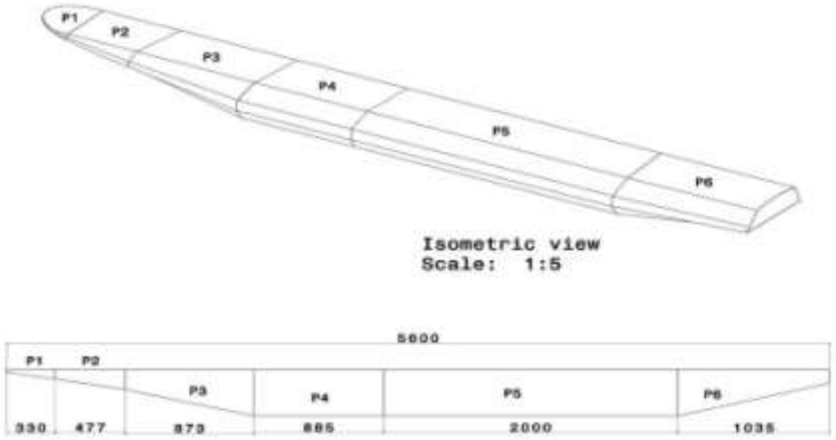


Figure 1: Design of hypersonic air-breathing cruise vehicle airframe

The fore body consists of two ramps, 11.86° and 13.75° and is designed for the cruise mach no.6 at 32km altitude. The configuration cross-section is flat on the bottom with chamfer on the sides and elliptical curvature on the top. There are chamfers on the top and bottom sides. The after body of length 1.035m consists of single expansion nozzle. The nose tip of the vehicle is blunt and spherical in shape.

Section	P1	P2	P3	P4	P5	P6
Length (mm)	330	477	873	885	2000	1035

Table 1: Length of sections of cruise vehicle

3.1 DESIGN OF P4 SECTION OF CRUISE VEHICLE

Section P4 has constant cross section throughout its length is designed for housing the fuel tank, air bottles and intake cowl opening mechanism. This section is 885mm long and lies between stations 1680mm and 2565mm as shown in figure 4.1. It has two end bulkheads, four stringers and four panels. The two end bulkheads are initially joined together by four stringers with help of fasteners. Then all four panels of thickness 3mm are placed over them and held by rivets/screws. The solid model of the section P4 is shown in figure 4.3. The section has been modelled in CATIA V5 and imported to Ansys Workbench.

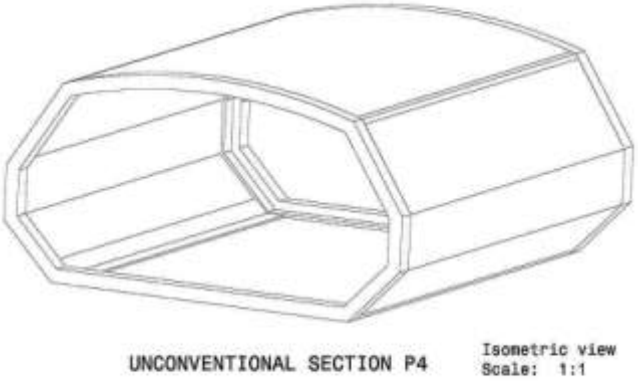


Figure 2: Section P4 of cruise vehicle

3.2 INPUT LOAD DATA

The current project is design of unconventional section for structural and thermal loads. The bottom portion of the section experiences high temperature as it acts as intake for Scramjet engine. The vehicle is cruised at free flight condition using the propulsion produced by Scramjet engine. At this free flight condition, flight loads and thermal loads act on the cruise vehicle which are as discussed below.

FLIGHT LOADS

Flight load analysis of cruise vehicle has been done at 2 instances of flight i) Control surface is not deflected where Maximum bending moment is 6300 N-m and ii) Control surface is deflected to 15° where Maximum bending moment is 6900 N-m.

THERMAL LOADS

As the total operational environment of the cruise vehicle is in high Mach regime which indicates that high temperatures are inevitable. To withstand these high temperatures, proper material selections and design has to be done. The Table 2 shows the temperatures applied at different panels of thickness 3mm each.

Panel	Top panel	Top slope panel	Vertical panel	Bottom slope	Bottom panel
Temperature (℃)	110	85	145	225	590

Table 2: Temperatures at different panels

4. MATERIAL PROPERTIES

A number of engineering materials have been studied for design. Following are two candidate materials with their limitation on mechanical properties at elevated temperatures. Because of light weight and high specific strength at operating temperature of airframe, Al alloy has been considered as material for Bulkheads, top panel, side panels and Ti alloy for bottom panel.

S.No	Properties	Al alloy	Ti alloy
1	Density	2700 kg/m^3	4560 kg/m^3
2	Temperature	300°C	700°C
3	Thermal conductivity	239 W/m-K	17 W/m-K
4	Coeff. Of Thermal Expansion	24e-6 K^{-1}	9.4e-6 K^{-1}
5	Ultimate Tensile Strength, MPa	333 at 300°C	265 at 600°C
		407 at 250°C	750 at 400°C
6	Young's modulus, MPa	53567 at 300°C	84000 at 600°C
		60786 at 250°C	122000 at 400°C

Table 3: Mechanical properties of materials

5. DESIGN METHODOLOGY

Modelling of the section P4 has been carried out using powerful tool CATIA V5. Section P4 has constant cross section throughout its length is designed for housing the fuel tank, air bottles and intake cowl opening mechanism. This section is 885mm long and lies between stations 1680mm and 2565mm as shown in figure 1. It has two end bulkheads, four stringers and four panels. The two end bulkheads are initially joined together by four stringers with help of fasteners. Then all four panels of thickness 3mm are placed over them and held by rivets/screws.

S.No	Part	Width (mm)	Thickness (mm)	Length (mm)
1	Bulkhead	65	25	Around the cross section
2	Stringer	25	6.5	885
3	Top panel	586.42	3	885
4	Top slope panel	191	3	885
5	Vertical panel	100	3	885
6	Bottom slope panel	141.36	3	885
7	Bottom panel	600	3	885

Table 4: Dimension specifications of P4 section of cruise vehicle

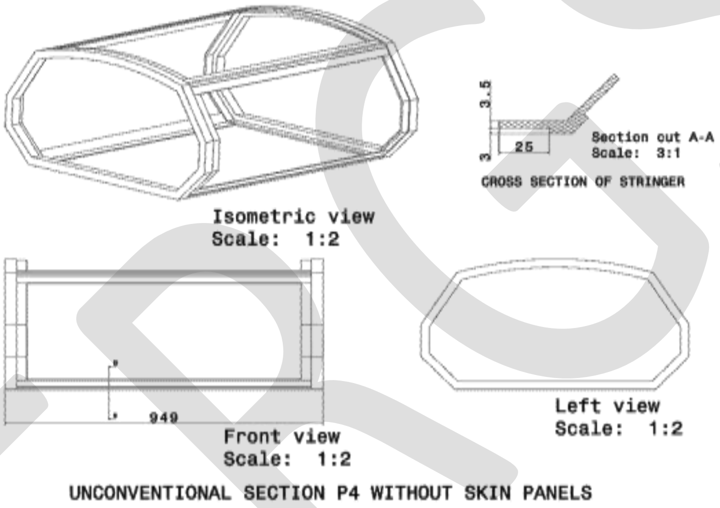
Geometrical configurations of bulkhead and stringer are given in figure 3. It shows the recess made on it to accommodate the panels of thickness 3mm.

CROSS SECTION OF BULKHEAD

CROSS SECTION OF STRINGER

Figure 3: Geometrical configurations of bulkhead and stringer

The orthographical representation of section P4 of hypersonic air-breathing cruise vehicle is shown in figure 4 below.



UNCONVENTIONAL SECTION P4 WITHOUT SKIN PANELS

Figure 4: Arrangement of bulkheads and stringers of section

6. ANALYTICAL METHOD

In this section of work, the stresses induced in the section due to bending moment load were found out. For this method the section is approximated as free-free beam. Hence, the theory of symmetrical bending of beams can be applied to calculate the stresses and deformation. In this flight load analysis, two cases are considered as discussed in the previous section.

ASSUMPTIONS

a) The section has been assumed as monocoque shell.
b) Thermal barrier coating (TBC) technology is available. A temperature reduction of 250°C across coating is achieved.

6.1 SYMMETRICAL BENDING

Symmetrical bending arises in beams which have either singly or doubly symmetrical cross-sections as in our case the cross-section is symmetrical about y-axis as shown in figure 5. The direct stress due to bending moment in the beam is given by the equation

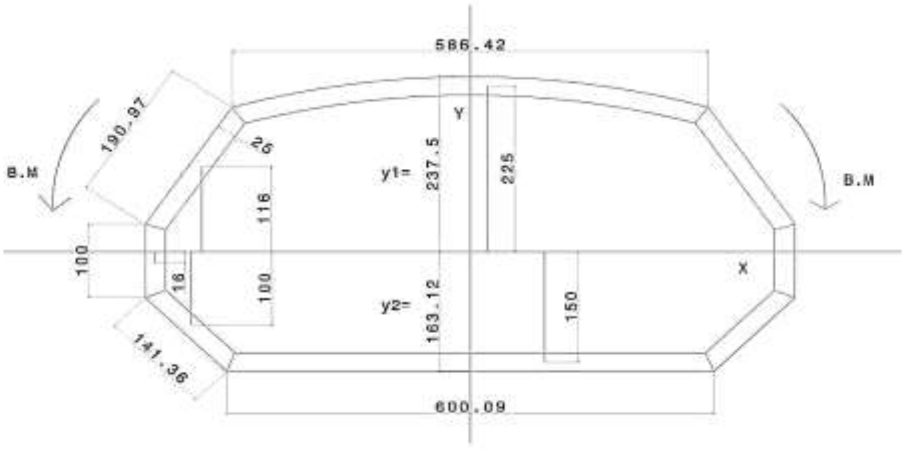
$$\sigma z = M/Z$$ [10]

$$Z = I/y$$

Where σz is direct stress, M is bending moment, Z is section modulus, I is moment of inertia, y is the position of neutral axis,

Moment of Inertia

For calculating the moment of inertia of the shelled section, it was divided into individual simple shells of standard geometry shapes. The moment of inertia of all these individual entities about their centroids was computed and then transferred to the centroid of the total section.



Bending moment acting on cross-section of P4

Figure 5: Geometrical configuration of cross section

Moment of inertia calculated for the panels is as shown below:

S.No	**Panel**	**I** (mm^4)	**Ix** (mm^4)
1	Top panel	763541.67	742926041
2	Top slope panel	10522462.22	74774862.22
3	Vertical panel	2083333.33	2723333.33
4	Bottom slope panel	1757281.14	37097581.14
5	Bottom panel	781250	338281250

Total moment of inertia of complete section is **Ixx = 971590908.8mm^4**

Direct stress due to bending moment

- For Control surface not deflected (δ = 0°), the calculated direct stress is **σz = 1.54 MPa.**
- For Control surface deflected (δ = 15°), the calculated direct stress is **σz = 1.68 MPa.**

Factor of safety on Ultimate tensile strength in both the cases is greater than 5.

6.2 THERMAL STRESS

Thermal stress is a decrease in the quality of a material that occurs due to excessive changes in temperature. It occurs as a result of a non uniform distribution of temperature in different parts of the body and some restriction on the possibility of thermal expansion or contraction.

$$\sigma_{Th} = E\alpha\Delta T \ [11]$$

$$\Delta T = T - Ta$$

Where σ_{Th} = Stress due to temperature expansion (Pa), E = Young's Modulus (N/m^2), α = Coefficient of thermal expansion (K^{-1})
ΔT = Temperature difference (K), T = Max Temperature, Ta = Ambient Temperature.

Approximated thermal stress is calculated for the maximum temperature that is developed on the section. The maximum temperature developed on the bottom panel of the section is 590°C.

Case i: Without HiMAT (Highly maneuverable aircraft technology) 1200 PLUS paint on bottom panel	**Case ii:** With HiMAT (Highly maneuverable aircraft technology) 1200 PLUS paint on bottom panel

T = 590°C = 863K At 32km altitude Ta = -44.5°C = 228.5K ΔT = 634.5K σ_{Th} = **576.75 MPa** FOS = 265/576.75 = **0.45**	T = 340°C = 613K At 32km altitude Ta = -44.5°C = 228.5K ΔT = 384.5K σ_{Th} = **442 MPa** FOS = 750/442= **1.69**

Case i: Factor of safety on Ultimate tensile strength is 0.45 which is very much low hence it is suggested to use suitable thermal protection system such as HiMAT (Highly maneuverable aircraft technology) 1200 PLUS paint on the bottom panel, which can reduce the temperature, by 250°C for 2mm coat. With the use HiMAT paint maximum temperature developed on the bottom panel of the section is 340°C. Hence, with this reduction in temperature, the strength available with the same material is 750MPa.

Case ii: For this case, factor of safety on Ultimate tensile strength is > 1.5 which is within the limits. Hence, it is suggested to use suitable thermal protection system for the bottom panel.

7. COMPUTATIONAL ANALYSIS

Finite element analysis for the given section was dealt completely in FEM software ANSYS Workbench.

Importing the geometry and meshing

Start the ANSYS Workbench and select the required analysis system. Add the materials in the engineering data. Select the geometry and import the P4 section model which was created using CATIA V5. Catia model has been saved as stp file before importing to the Ansys Workbench. Select the model then it will be directed to the Ansys mechanical window where the problem will be solved. Imported model can be as shown in figure 6. Select the geometry, enter the element size as 0.03 and give smoothing as high to get a fine meshed model. Mesh has been created using the automatic meshing method. Meshed model can be as shown in figure 7.

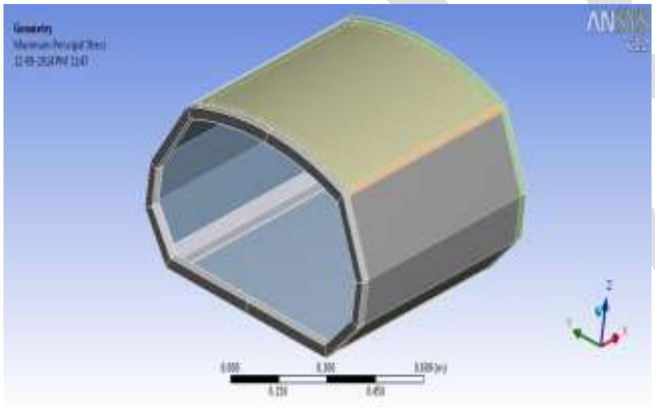


Figure 6: Section P4 model of cruise vehicle

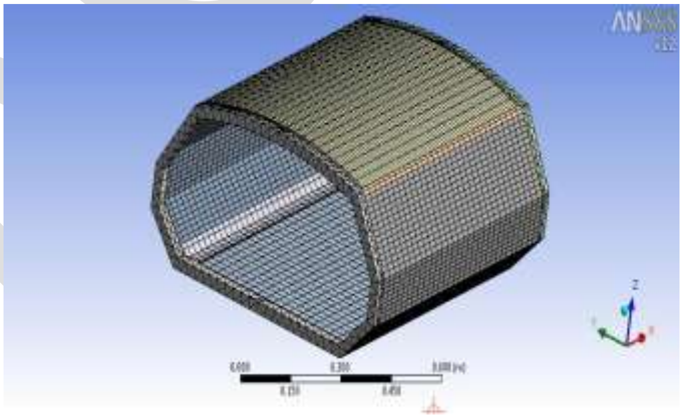
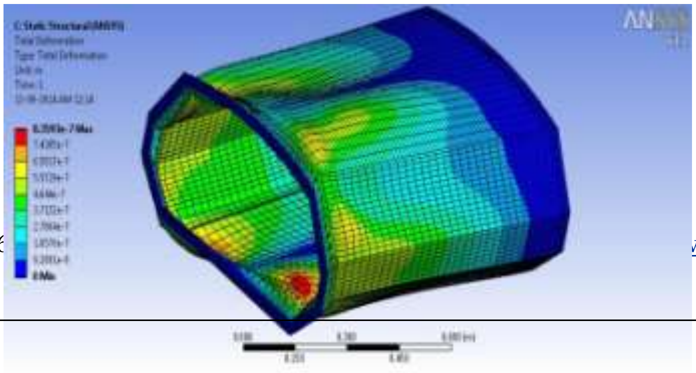


Figure 7: Meshed model

7.1 STATIC ANALYSIS

Static analysis of cruise vehicle has been done at 2 instances of flight i) Control surface is not deflected where Maximum bending moment is 6300 N-m and ii) Control surface is deflected to 15° where Maximum bending moment is 6900 N-m. Apply the Al alloy material to the bulkheads, top panel and side panel and Ti alloy material to the bottom panel of the model. Apply the fixed support on both ends of cross section to constrain the model in ALL DOF. Select the Moment, M = 6300 N-m for the case i and M = 6900 N-m for case ii and apply it on the model. Solve the problem to find the total deformation, von-Mises stress.



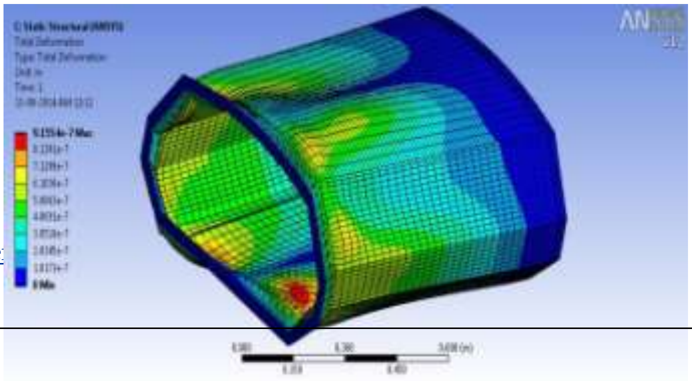


Figure 8: Deformation of the model at δ = 0°

Figure 9: Deformation of the model at δ = 15°

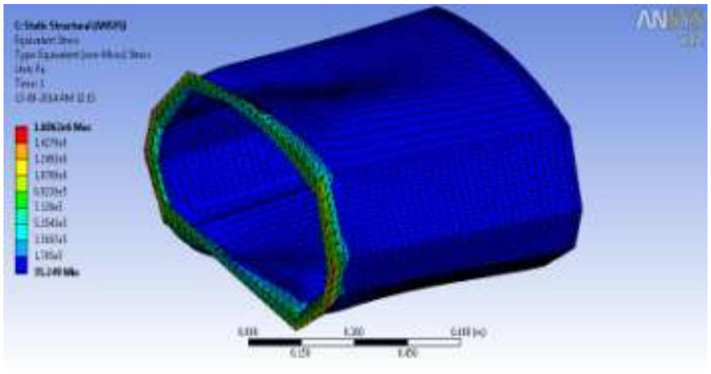


Figure 10: Von-Mises stress of the model at δ = 0°

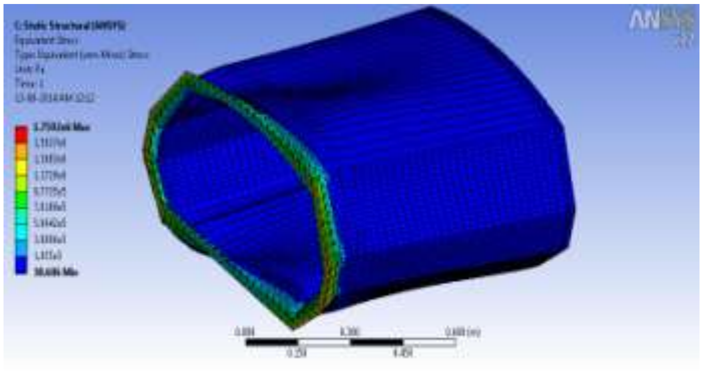


Figure 11: Von-Mises stress of the model at δ = 15°

7.2 STEADY-STATE THERMAL ANALYSIS

Steady state thermal analysis has been performed for two cases: i) Without HiMAT (Highly maneuverable aircraft technology) 1200 PLUS paint on bottom panel and ii) With HiMAT (Highly maneuverable aircraft technology) 1200 PLUS paint on bottom panel. Apply the Al alloy material to the bulkheads, top panel and side panel and Ti alloy material to the bottom panel of the model. Apply the thermal loads on the panels as given in Table 2. For case ii change the temperature on bottom panel from 590°C to 340°C. Apply the convection 1 on the model except bottom panel and enter the value of film coefficient as 25 W/m^2 °C and ambient temperature as –44.5 °C. Now apply the convection 2 on the bottom panel and enter the value of film coefficient as 22 W/m^2 °C and ambient temperature as –44.5 °C. Solve the model to find the temperature distribution over the unconventional section.

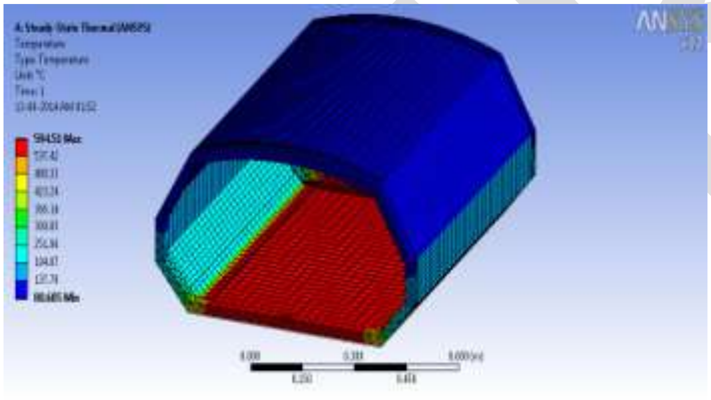


Figure 12: Temperature distributions for case i

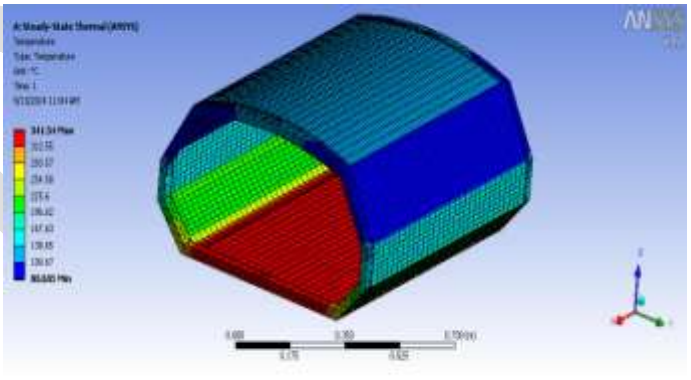
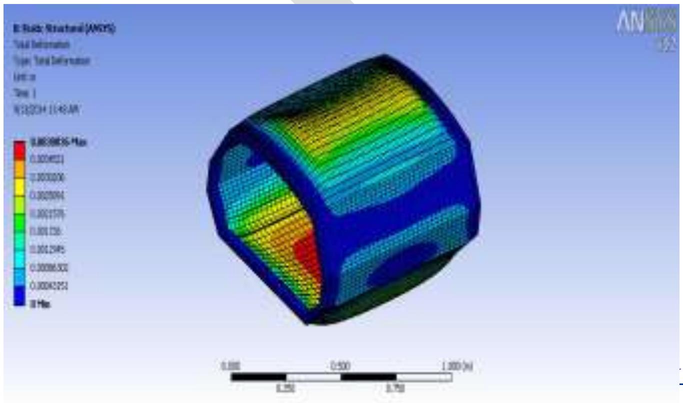


Figure 13: Temperature distributions for case ii

Now static structural analysis system is selected to find the thermal stresses due to temperature distributions. Apply the All DOF boundary condition to the cross section and solve the model to find the thermal stress and deformation of the unconventional section.



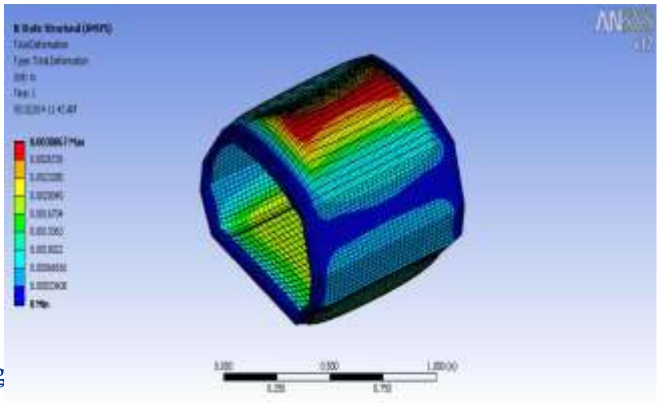
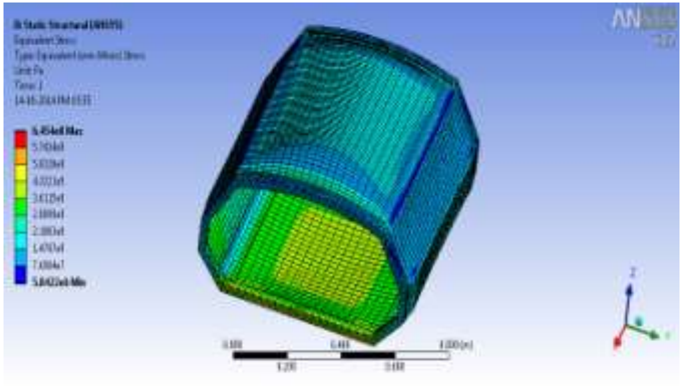


Figure 7.14: Deformation of the model for case i

Figure 7.15 Deformation of the model for case ii



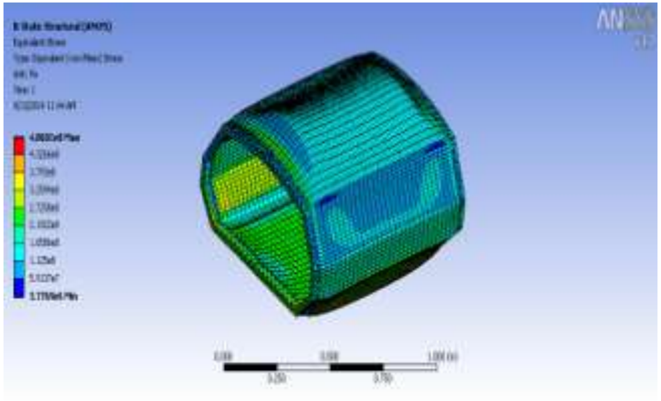


Figure 7.16 Von-Mises stress distribution for case i

Figure 7.17 Von-Mises stress distribution for case ii

7.3 COUPLED THERMO-STRUCTURAL ANALYSIS

Coupled thermo-structural analysis has been carried out for two cases: i) Control surface is not deflected where Maximum bending moment is 6300 N-m and ii) Control surface is deflected to 15° where Maximum bending moment is 6900 N-m. After finding out the temperature distribution over the unconventional section with HiMAT paint on bottom panel in thermal analysis switch to static structural analysis system. Apply the All DOF boundary condition to the cross section and Select the Moment, M = 6300 N-m for the case i and M = 6900 N-m for case ii and apply it on the model. Solve the problem to find the total deformation, von-Mises stress.

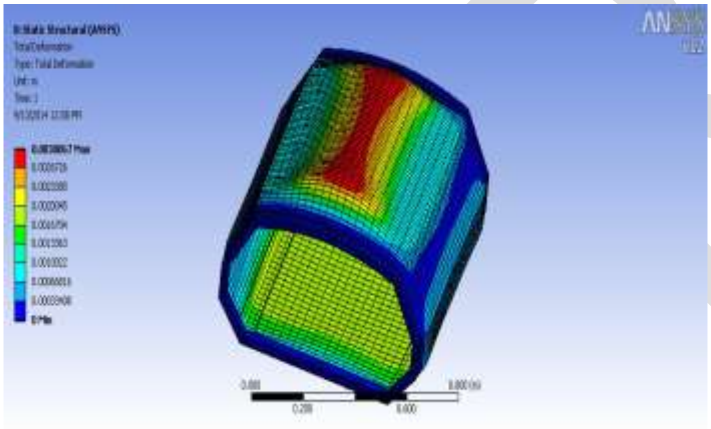


Figure 18: Deformation of the model at δ = 0°

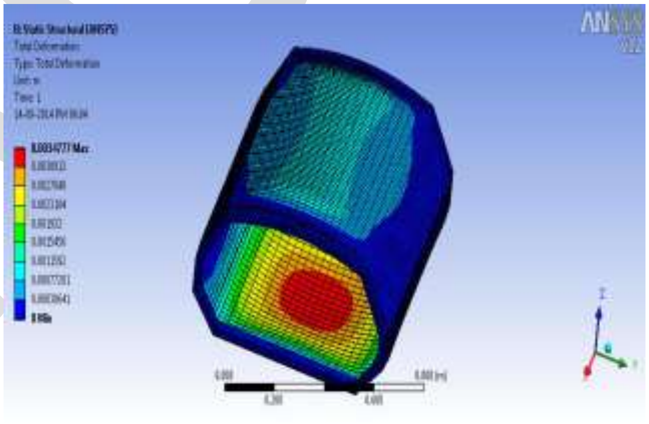


Figure 19: Deformation of the model at δ = 15°

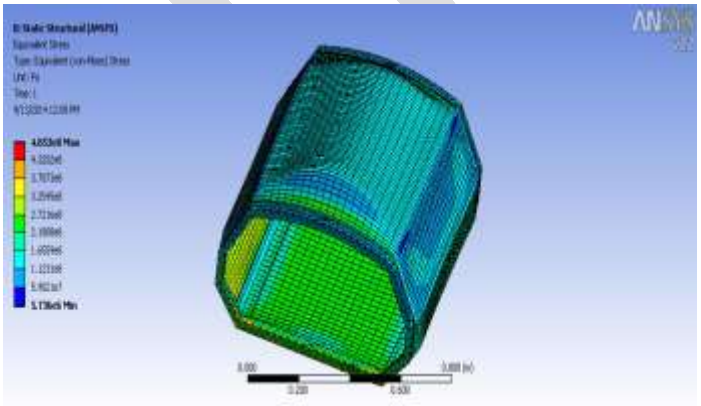


Figure 20: Von-Mises stress of the model at δ = 0°

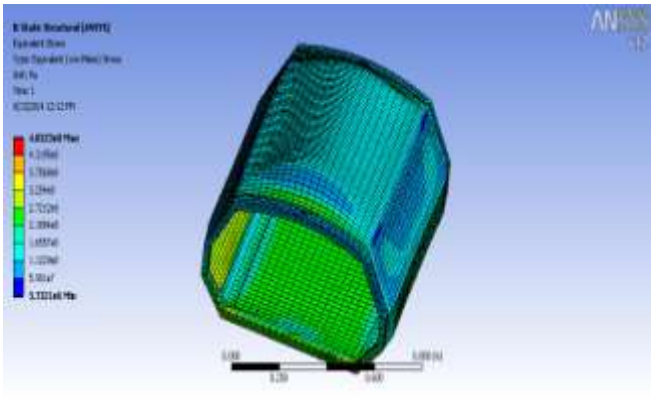


Figure 21: Von-Mises stress of the model at δ = 15°

8. RESULTS AND DISCUSSIONS

8.1 STATIC ANALYSIS RESULTS

Load Case	Mass (kg)	Maximum Deformation (m)	Maximum Stress (MPa)	Ultimate Tensile Strength (MPa)	Factor of Safety
control surface not deflected (δ = 0°)	31.56	8.35e-7	1.6	265 at 600°C	165
control surface deflected (δ = 15°)	31.56	9.15e-7	1.75	265 at 600°C	151

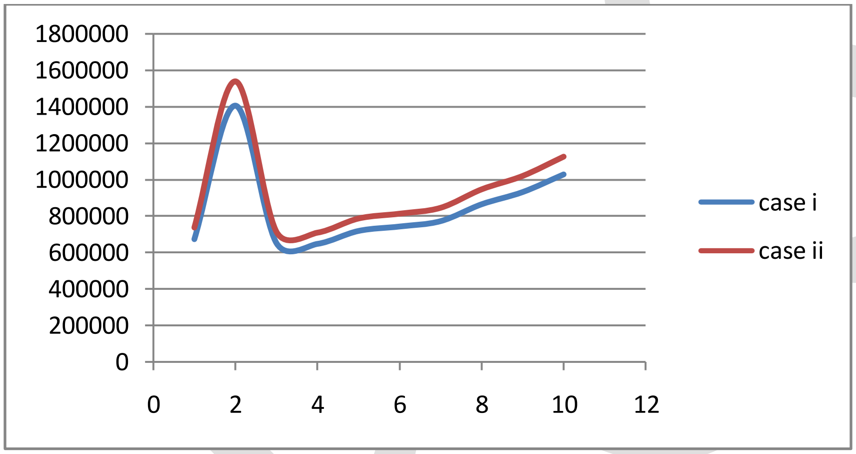


Figure 22: Stress variation for both cases

Observation: Factor of safety on Ultimate tensile strength for the model is greater than 5 in both the cases.

8.2 THERMAL ANALYSIS RESULTS

Case	Mass (kg)	Maximum Deformation (m)	Maximum Stress (MPa)	Ultimate Tensile Strength (MPa)	Factor of Safety
Without HiMAT paint	31.56	0.0038	607	265 at 600°C	0.436
With HiMAT paint	31.56	0.003	463	750 at 400°C	1.61

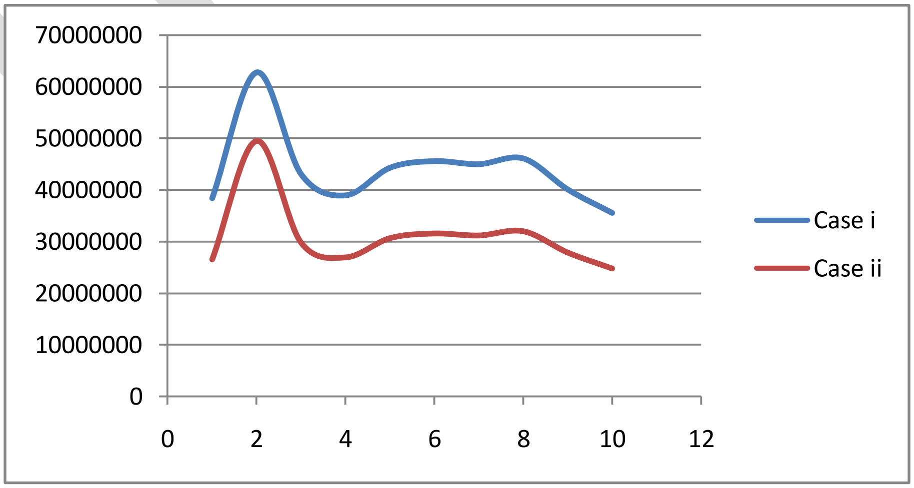


Figure 23: Stress variation for both cases

Observation: Factor of safety on Ultimate tensile strength for case-i is less than 1.5 and for case-ii is greater than 1.5.

8.3 COUPLED THERMO-STRUCTURAL ANALYSIS RESULTS

Load Case	Mass (kg)	Maximum Deformation (m)	Maximum Stress (MPa)	Ultimate Tensile Strength (MPa)	Factor of Safety
control surface not deflected (δ = 0°)	31.56	0.00307	485.2	750 at 400°C	1.545
control surface deflected (δ = 15°)	31.56	0.0034	485.3	750 at 400°C	1.54

Observation: Factor of safety on Ultimate tensile strength for the material in both the cases is greater than 1.5.

8.4 RESULT VALIDATION

FLIGHT LOAD ANALYSIS

Load case	Analytical Stress (MPa)	Computational Stress (MPa)	% Error
control surface not deflected (δ = 0°)	1.54	1.6	4.28
control surface deflected (δ = 15°)	1.68	1.76	4.76

Observation: In both the load cases there is a good agreement between Analytical and Computational results.

THERMAL LOAD ANALYSIS

Ti alloy	Analytical Stress (MPa)	Computational Stress (MPa)	% Error
Without HIMAT paint	577	607	5.19
With HIMAT paint	442	463	4.75

Observation: In both the cases there is a good agreement between Analytical and Computational results.

CONCLUSION

Because of light weight and high specific strength at operating temperature of airframe, Al alloy has been considered as material for Bulkheads, top panel, side panels and Ti alloy for bottom panel with suitable thermal protection system. Mass of airframe of the section of hypersonic air-breathing cruise vehicle is found to be 31.56 kg. Maximum deformation and von mises stress of unconventional section of hypersonic cruise vehicle is 3.4 mm and 485.3 MPa which are in safe limit. Maximum deformation and maximum obtained stresses of unconventional section are within the design limit so our model is safe at the given operating conditions.

FUTURE SCOPE OF WORK

1. The study can be extended by analyzing the other sections of Cruise vehicle.
2. The more accurate analysis of this section can be done by including the rivets at the intersection of joints.
3. Harmonic and modal analysis can be carried out to find natural frequency and mode shape of the component.

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