

BRAZILIAN 14-X HYPERSONIC WAVERIDER UNPOWERED SCRAMJET AEROSPACE VEHICLE STRUCTURAL ANALYSIS AT MACH NUMBER 7

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Abstract. *The Brazilian VHA 14-X is a technological demonstrator of a hypersonic airbreathing propulsion system based on supersonic combustion (scramjet) to fly at Earth's atmosphere at 30km altitude at Mach number 10, designed at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, at the Institute for Advanced Studies. Basically, scramjet is a fully integrated airbreathing aeronautical engine that uses the oblique/conical shock waves generated during the hypersonic flight, to promote compression and deceleration of freestream atmospheric air at the inlet of the scramjet. Scramjet is an aeronautical engine, without moving parts, therefore it is necessary another propulsion system to accelerate the scramjet to the operation conditions. Rocket engines are a low-cost solution to launch scramjet integrated vehicle to flight to the test conditions. The Brazilian two-stage rocket engines (S31 and S30) are able to boost the VHA 14-X to the predetermined conditions of the scramjet operation, 30km altitude but at Mach number 7. Therefore, it is needed to design the structure of the VHA 14-X waverider to support the aerodynamic loads during the atmospheric hypersonic flight at the same conditions. One-dimensional theoretical analysis, applied at 30km altitude at Mach number 7, provide the pressure distribution on the VHA 14-X waverider upper and lower surfaces. Structural materials for the stringers and ribs as well as coating materials for the thermal protection systems were specified based on preliminary studies. ANSYS Workbench software, which provides the Structural Numerical Analysis using Finite Element Method, has been applied to the structural analysis of the VHA 14-X waverider unpowered scramjet at 30km altitude at Mach number 7. Stress field, strains and deformations are presented.*

Keywords: VHA 14-X, waverider, scramjet, structural analysis

1. THE BRAZILIAN 14-X HYPERSONIC AEROSPACE VEHICLE

The 14-X Hypersonic Aerospace Vehicle, VHA 14-X (Fig. 1), named after 14-Bis developed by aviation pioneer Alberto Santos Dumont, was designed to fly at Earth's atmosphere at 30km altitude at Mach number 10, at Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, at Institute for Advanced Studies (IEAv).

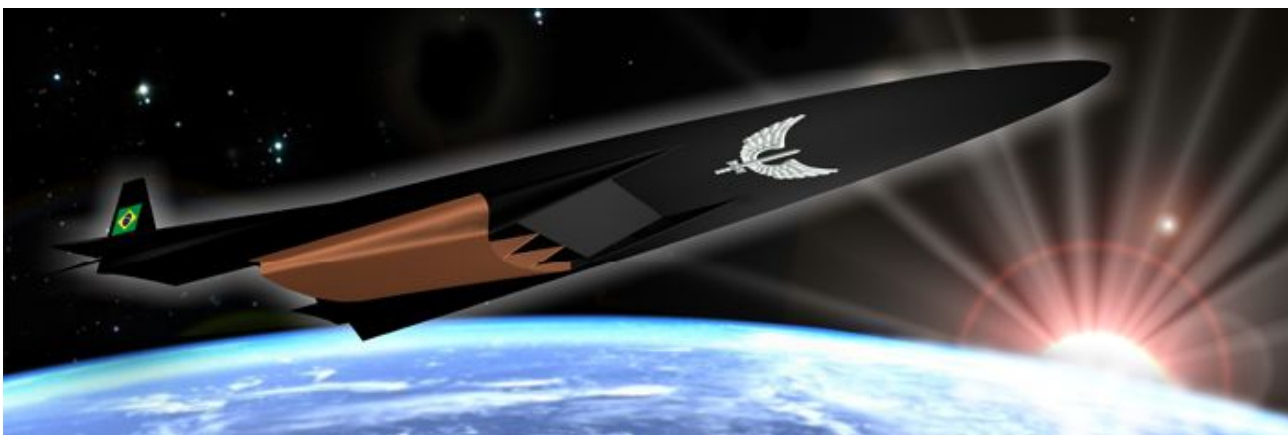


Figure 1: 14-X Hypersonic Aerospace Vehicle.

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The VHA 14-X is part of the continuing effort of the Department of Aerospace Science and Technology (DCTA) to design, to develop, to manufacture and to demonstrate, in free flight, a technology demonstrator at Mach number 10 at 30km altitude (Ricco et al., 2011; Toro et al., 2012), using: i) "waverider" technology to provide lift to the aerospace vehicle, and ii) "scramjet" technology to provide hypersonic airbreathing propulsion system based on supersonic combustion.

Aerospace vehicle using waverider technology (Fig. 2) could be defined as a supersonic or a hypersonic vehicle which uses the high pressure zone on its lower surface caused by leading-edge attached shock wave to generate lift surface. Therefore, the attached shock wave in a sharp leading edge isolates the high pressure zone (lower surface) from the low pressure zone (upper surface), which inhibits the flow spillage. In general, the upper surface is aligned with the free stream hypersonic flow. Atmospheric air, pre-compressed by the leading-edge attached shock wave, which lies between the sharp attached leading edge shock wave and lower vehicle surface may be used in hypersonic airbreathing propulsion system based on "scramjet" technology.

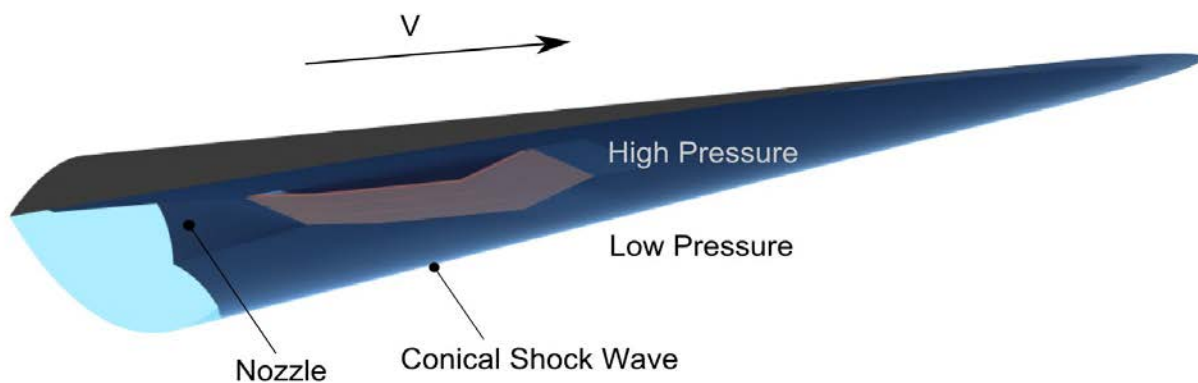


Figure 2: Waverider vehicle concept.

The VHA 14-X pure waverider (Fig. 3) surface (Rolim 2009, Rolim et al. 2009, 2011) was designed to fly at Earth's atmosphere at 30km altitude at Mach number 10 based on Rasmussen et al. (1990) concept, which is derived from a supersonic flow past a cone (Fig. 4) with the volumetric efficiency and the viscous high lift-to-drag ratio as optimization parameters. Later, Rolim (2009) and Rolim et al. (2009; 2011) added a compression and expansion ramps (Fig. 5) to the pure waverider surface in order to simulate the flow on a scramjet engine. The 14.5° deflection compression ramp is designed to capture the entire air flow compressed by the 5.5° waverider leading edge and to provide the ideal conditions for the supersonic combustion of the hydrogen, while the expansion section is assumed a 15° ramp.

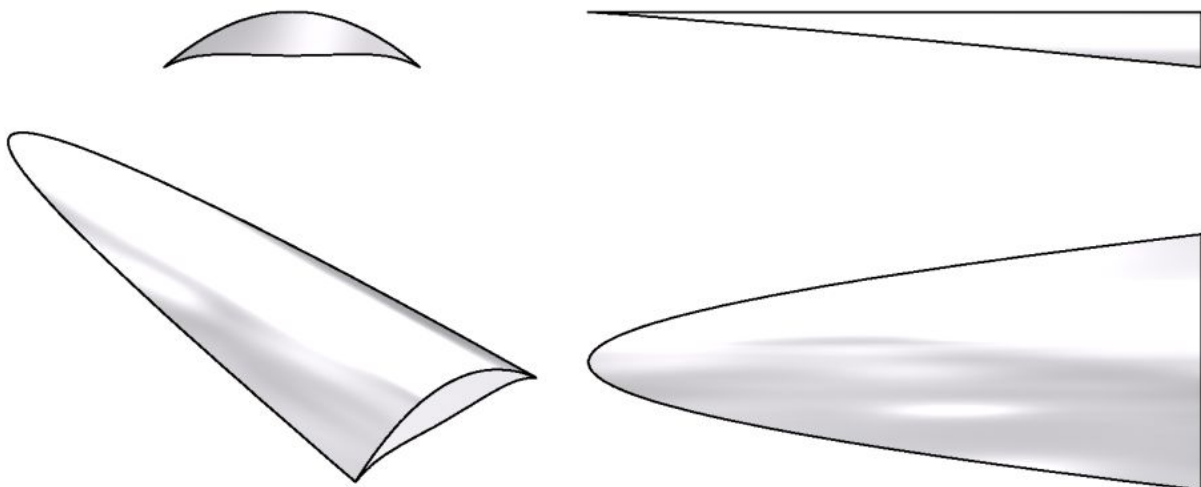


Figure 3: The 14-X pure waverider surface.

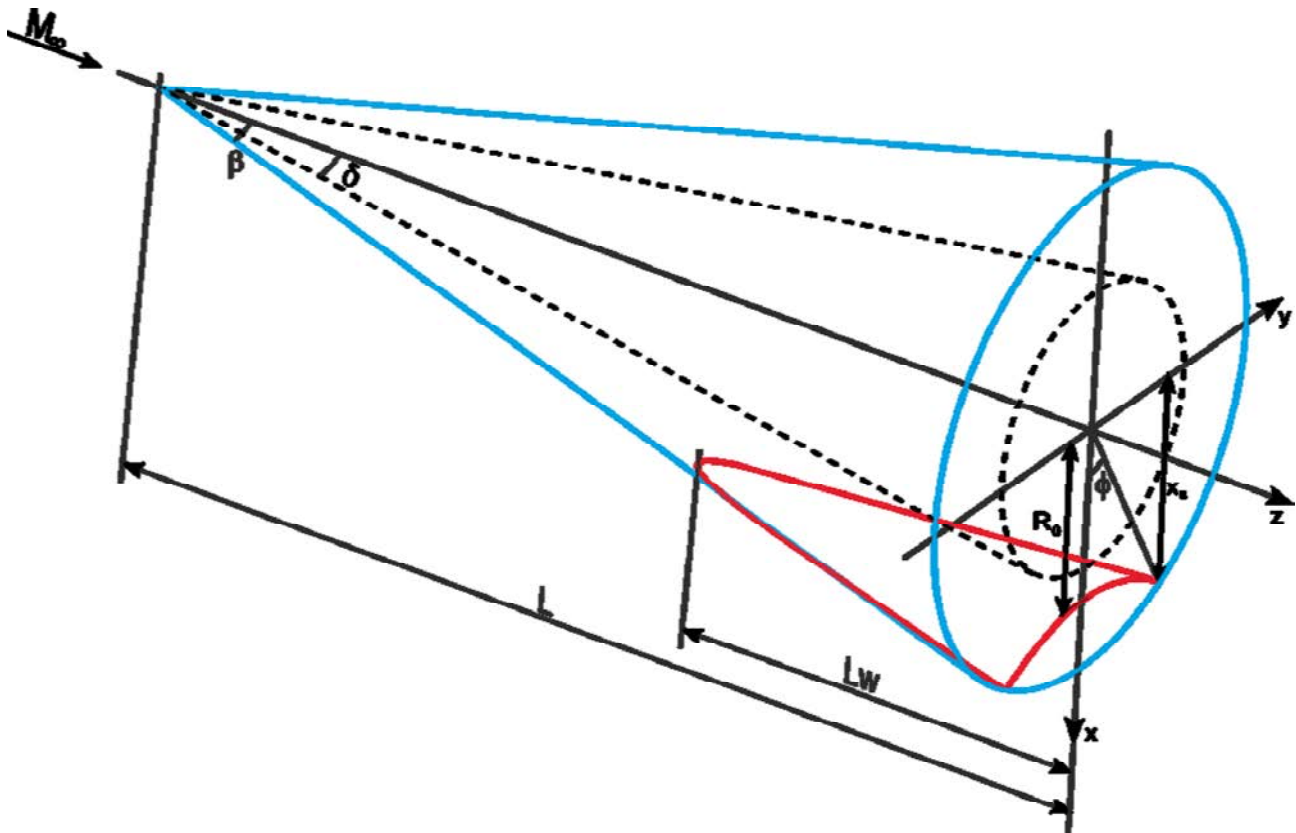


Figure 4: Schematic view of construction of the axisymmetric cone-derived waverider.

A 718.28-mm. long stainless steel “waverider” model, with 5.5° waverider leading edge, 14.5° deflection compression ramp and 15° expansion ramp drawn by Costa (2011) and Costa et al. (2012, 2013), instrumented with seven piezoelectric pressure transducers on the compression surface, was experimental investigated (Rolim 2009, Rolim et al. 2009, 2011) on the equilibrium interface mode operation at the IEAv 0.60-m. nozzle exit diameter Hypersonic Shock Tunnel T3 at freestream Mach number from 8.9 to 10 with stagnation pressures between 2176-2938 psi and temperatures at the range of 1558-2150 K. Furthermore, the free stream conditions were such that $Re_\infty = 2.25 \text{ to } 8.76 \cdot 10^6 \text{ (m}^{-1}\text{)}$ and $Kn_\infty = 0.06 \text{ to } 0.19$. Schlieren photographs taken at the 5.5° waverider leading edge

and at the 14.5° deflection compression ramp provide enough experimental data to design the scramjet, which was coupled at the lower surface of the 14-X Hypersonic pure waverider Aerospace Vehicle between the end of the 14.5° deflection compression ramp and the beginning at the 15° expansion ramp.

Hypersonic airbreathing propulsion, which uses supersonic combustion ramjet (scramjet) technology (Fig. 5) offers substantial advantages to improve performance of aerospace vehicle that flies at hypersonic speeds through the Earth’s atmosphere, by reducing onboard fuel. As a matter of fact, at hypersonic speeds, a typical value for the specific impulse of a H_2 - O_2 rocket engine is about 400s, while the specific impulse of a H_2 fueled scramjet is 2000s to 3000s. In fact, the use of atmospheric air as oxidizer allows air breathing propulsion vehicles to substantially increase payload weight. Basically, scramjet is a fully integrated airbreathing aeronautical engine that uses the oblique/conical shock waves generated during the hypersonic flight, to provide compression and deceleration of freestream atmospheric air at the inlet of the scramjet.

Fuel, at least sonic speed, may be injected into the supersonic airflow just downstream of the inlet or at the beginning of the combustion chamber. Right after, both oxygen from the atmosphere and on-board hydrogen fuel are mixed. The combination of the high energies of the fuel and of the oncoming hypersonic airflow starts the combustion at supersonic speed. Finally, the divergent exhaust nozzle at the afterbody vehicle accelerates the exhaust gases, creating thrust. As mentioned early, atmospheric air, pre-compressed by 5.5° pure waverider leading-edge following compressed by 14.5° deflection compression ramp may be used in hypersonic airbreathing propulsion system based on “scramjet” technology.

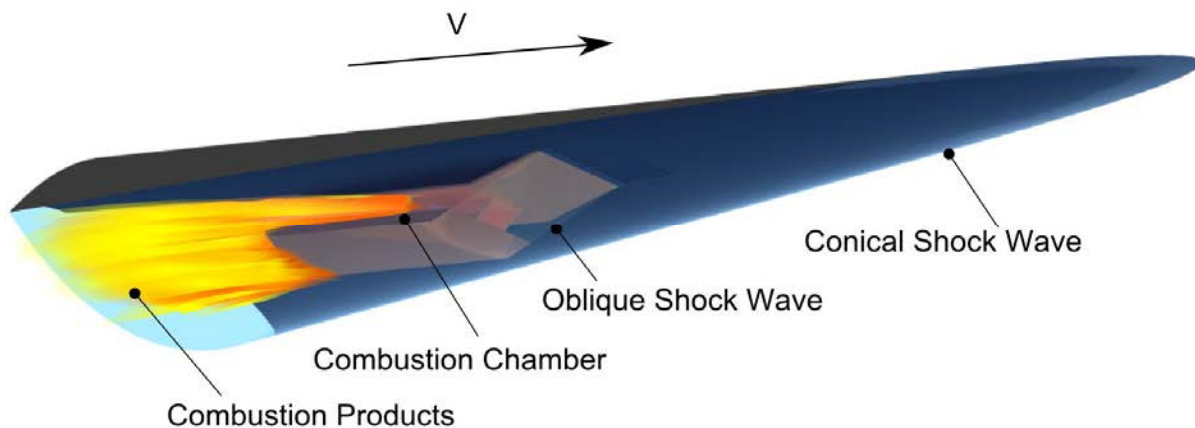


Figure 5: Scramjet hypersonic airbreathing propulsion concept.

A 265.1-mm. long, 80-mm. wide and 35-mm. high combustion chamber model, based on the numerical (Hyslop, 1998) and on the experimental (Kasal et al., 2002) works, was coupled at the lower surface of the truncated 14-X Hypersonic waverider Aerospace Vehicle between the end of the 14.5° deflection compression ramp and the beginning at the 15° expansion ramp. Experimental investigation was performed at the T3 Hypersonic Shock Tunnel. Schlieren photographs provide sufficient data to design a 2-m. long VHA 14-X waverider scramjet (Fig. 6) to flight at 30km altitude at Mach number 10.

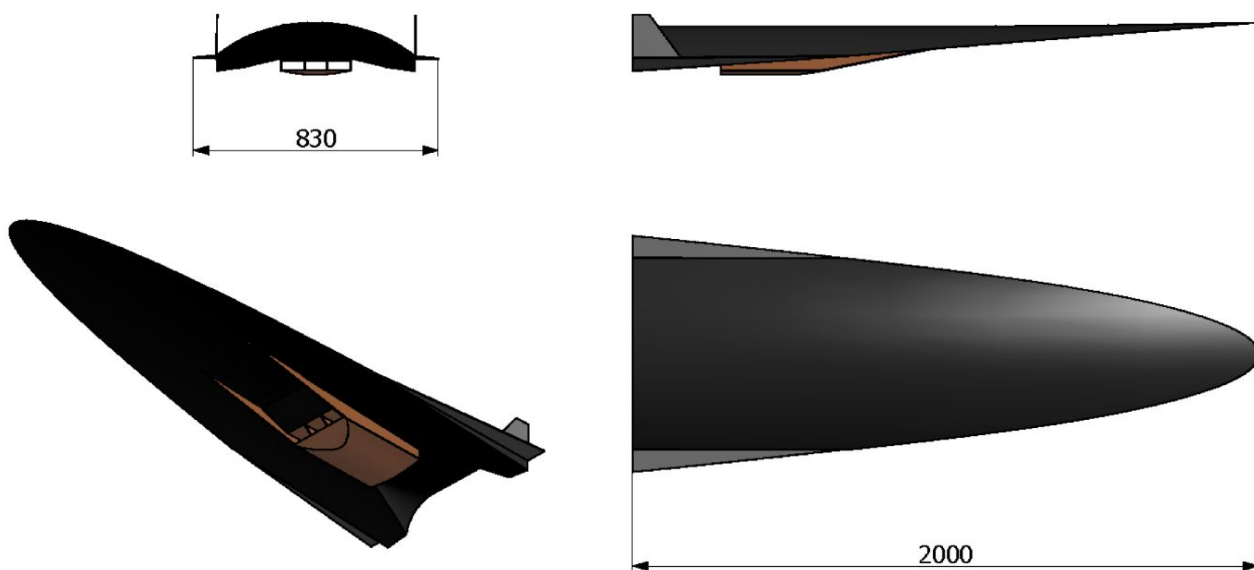


Figure 6: Dimensional for the 14-X Hypersonic Aerospace Vehicle.

Despite of the VHA 14-X was designed to demonstrate the scramjet technology at 30km altitude at Mach number 10, the coordination of the VHA 14-X project decided as a low-cost Brazilian solution to launch scramjet integrated vehicle to fly the VHA 14-X to the test conditions at 30km altitude at Mach number 7, using the Brazilian solid rocket engines (S31 and S30), in ballistic trajectory. Such approach may provide an affordable path for maturing of the Brazilian hypersonic airbreathing components and systems in flight.

The Brazilian Hypersonic Accelerator Vehicle which is composed by two-stage, unguided, rail launched, solid rocket engines will be used to accelerate the VHA 14-X to the predetermined conditions of the scramjet operation (Fig. 7) i.e., position (altitude, latitude and longitude), speed (Mach number), dynamic pressure and angle of attack from the Alcântara Launch Center. The VHA 14-X will separate, at 30km altitude, from the 2nd stage rocket engine of the Hypersonic Accelerator Vehicle. The scramjet will be operational for about 4-5 seconds in upward flight of the VHA 14-X. After scramjet engine demonstration is completed, the VHA 14-X will follow the ballistic flight. After reaching the apogee, the VHA 14-X will follow the descending flight to splash into the Atlantic Ocean. Both Hypersonic Accelerator Vehicle and 14-X Hypersonic Vehicle will not be recovered. The Alcântara Launch Center (CLA) is a satellite launching base of the Brazilian Space Agency (AEB), located at the Latitude 2° 18' S Longitude 44° 22' W, on Brazil's northern Atlantic coast, outside São Luis city (capital of Maranhão State).

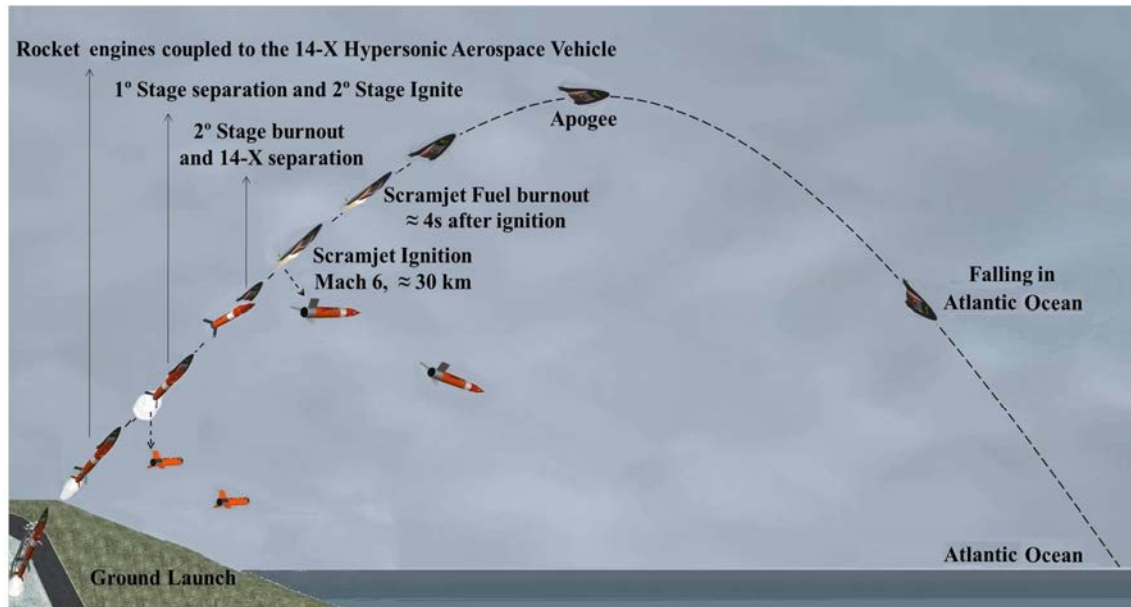


Figure 7: VAH and VHA 14-X in ballistic trajectory.

2. CONDITION NEEDED TO PERFORM STRUCTURAL ANALYSIS OF THE VHA 14-X AT MACH 7

As mentioned early, the VHA 14-X requires a Hypersonic Accelerator Vehicle to deliver it to the scramjet engine test condition. The S31 and S30 unguided, rail launched, solid rocket engines, which are developed and manufactured by the Institute of Aeronautics and Space (IAE/DCTA) will be used for the first atmospheric flight as planned for VHA 14-X captive scramjet-unpowered Mach number 7.

First, the one-dimensional analytic theoretical Analysis, based on no viscous (boundary layer) compressible (perfect gas) airflow (Anderson, 2003) and Prandtl-Meyer expansion flow (Anderson, 2003) theories were applied to the upper and lower surfaces of the VHA 14-X (Fig. 8) to determine the thermodynamics properties not only to design the VHA 14-X but also to provide the pressure distribution for structural purpose analysis.

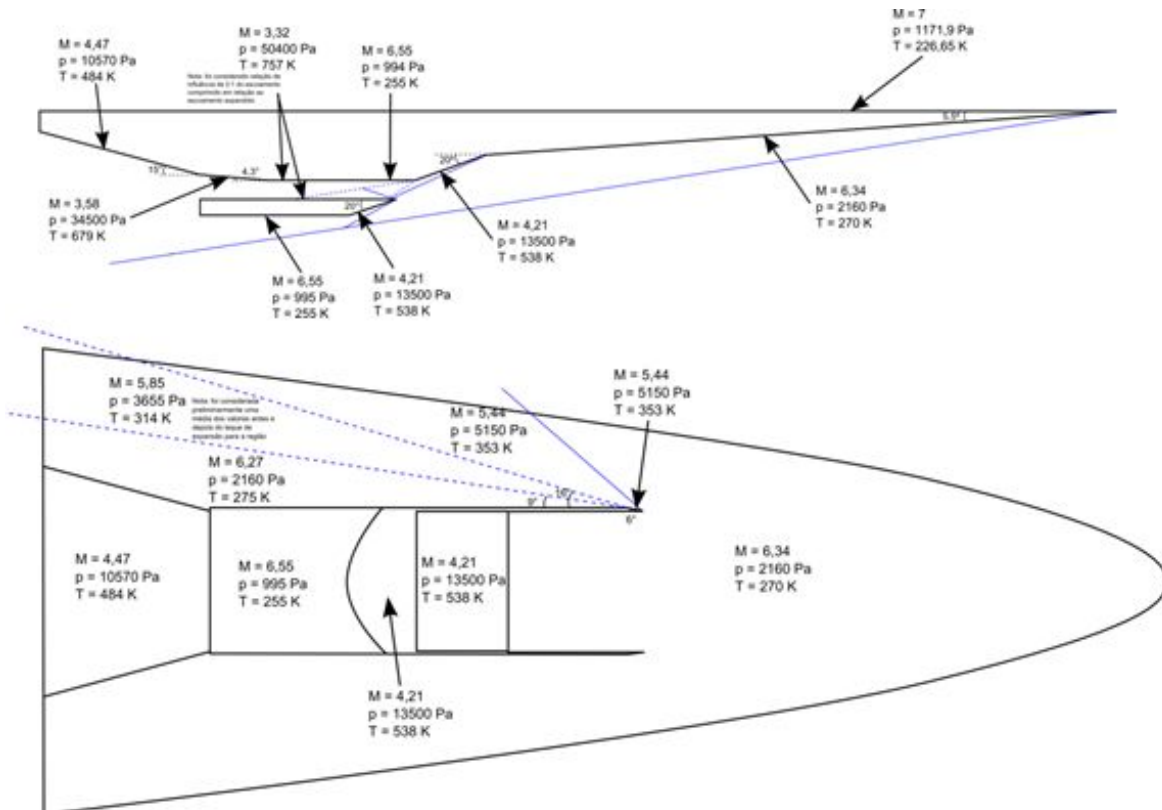


Figure 8: VHA 14-X Analytic Theoretical Analysis at 30km altitude at Mach 7.

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Next, internal configuration using stringers and ribs for structural materials as well as coating materials for the thermal protection systems were specified based on preliminary studies (Fig. 9). Also, materials (Fig. 10) were specified based on the materials used in the X-43 (Harsha et al., 2005) and in the X-51 (Hank et al., 2008) U.S. hypersonic demonstrators. Should be mentioned the materials are available in Brazil and they are used at the Brazilian vehicle VSB-30 (Heitkoetter, 2009).

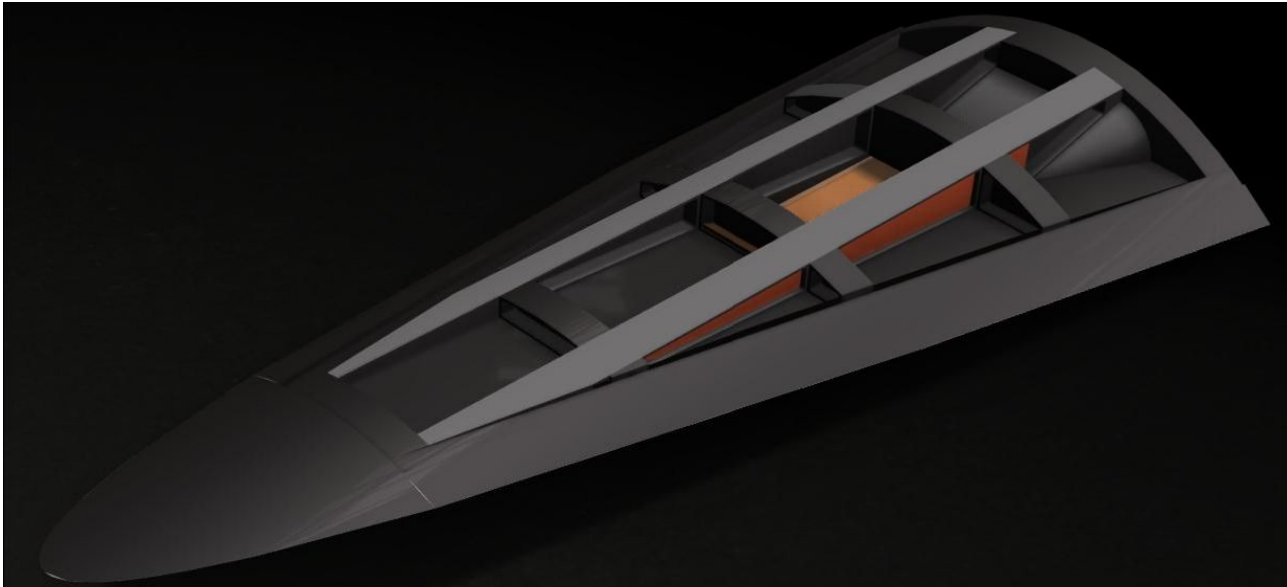


Figure 9: VHA 14-X waverider scramjet internal configuration.

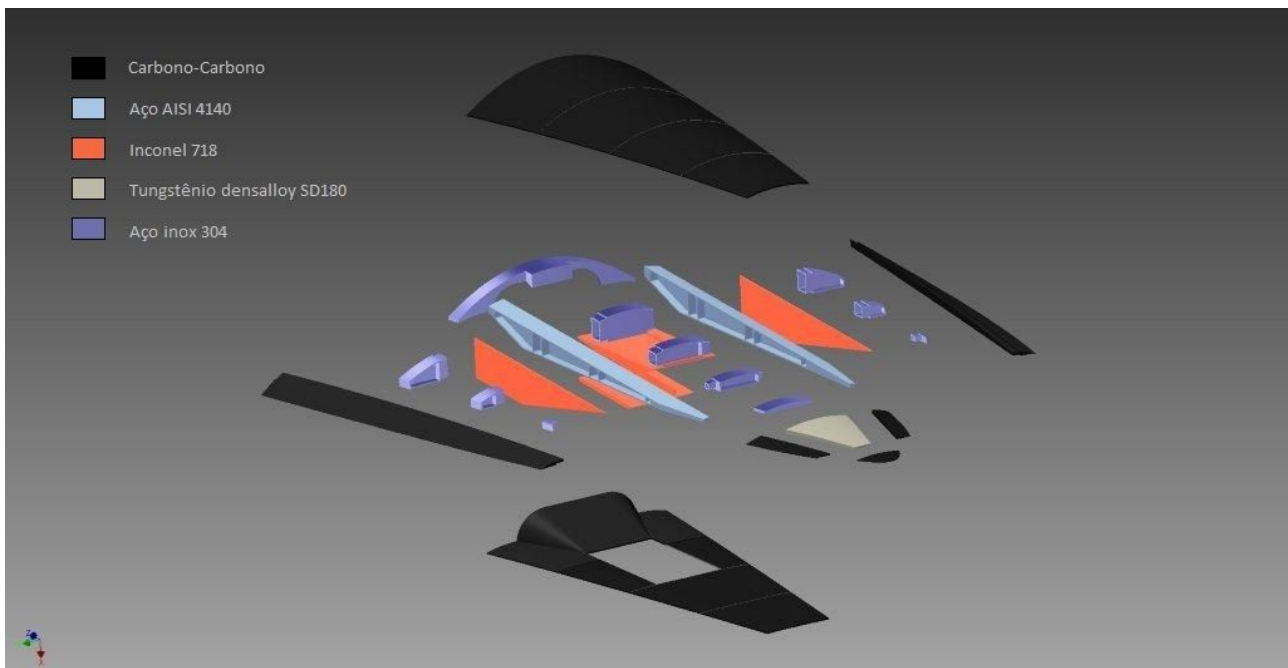


Figure 10:- VHA 14-X waverider scramjet material specification and lay-out.

3. STRUCTURAL NUMERICAL ANALYSIS

Due to the high complexity of aerospace structures, which consist of a combination of different structural elements (stringers, ribs, panels, etc.) and of different types of materials, these structures cannot be described neither approximated by a mathematical equation, invalidating the use of classical methods of structural analysis. Therefore, it is necessary the use of the Finite Element Methods (FEM) to describe of high complexity structures into simpler and easier algebraic equations (Lage 2009). Additionally, numerical methods should be used due to the high degree of programmability of the FEM, to obtain greater speed and accuracy in calculations of the matrix associated.

Therefore, Structural Numerical Analysis using Finite Element Method (ANSYS Workbench software, 2011) has been applied to the VHA 14-X waverider unpowered scramjet flying at 30km altitude at Mach number 7, considering

the dynamic pressure during the ballistic trajectory of the S31 and S30 unguided, rail launched, solid rocket engines and neglecting any nonlinearity (physical, geometric, material, etc.).

First, methodology for pre-processing and post-processing were defined to maximize efficiency in achieving the results of structural analysis of VHA-14 X coupled to rocket engines (S31 and S-30) flying at the altitude of 30km altitude and reaching at speed corresponding the Mach number 7. The pre-processing consists of the following steps: addition of materials (to be used in this project) at the software ANSYS library, application the APDL module for the carbon-carbon parts, definition the geometry of the VHA 14-X into ANSYS database, generation the mesh by ANSYS, optimization of the mesh by analyzing the quality of the generated mesh, dimensional parameterization, adding bond structures, determination and application of pressure loads.

The post-processing is made by analyzes of stress field and total displacement field together with the numerical error (APDL) of the mesh in order to optimize the thickness and weight reduction in the areas of low stress in the stringers as well as in the ribs. If necessary, propose changes in the geometry and again performing pre-processing and post-processing to obtain an appropriate solution.

The mesh generated by ANSYS Workbench (automatically) for the VHA 14-X showed the presence of distorted elements, which it is characteristic of structured mesh, and can generate results that do not match reality. Appropriate tools of the software ANSYS Workbench were used to structure the mesh. The optimized mesh (Fig. 11) containing 184632 nodes and 61619 elements (hexahedral and tetrahedral) was obtained using the geometry of VHA 14-X waverider at the Mach 10 (Fig. 6) implemented in the software ANSYS.

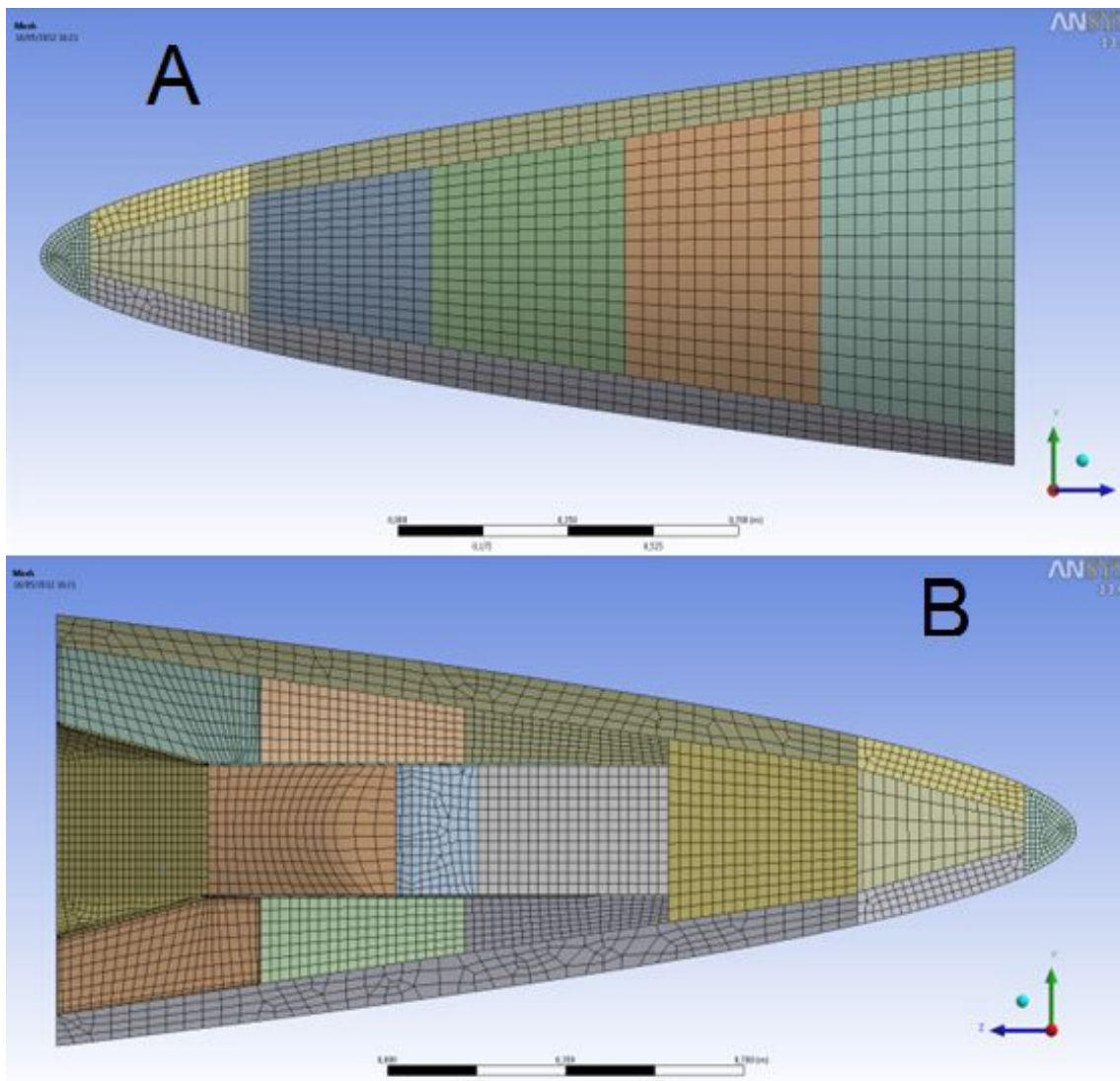


Figura 11: VHA 14-X optimized mesh.

Next, the isotropic (Table 1) and non-isotropic (Table 2) material mechanical properties specified by Costa, 2011) to be used at the structural and thermal protection systems of the VHA 14-X (Fig. 10) were inserted into ANSYS Workbench material database. The mechanical properties of the CRFC 3D orthogonal (Table 2) were obtained from Gonçalves (2008).

Table 1: Mechanical properties for isotropic materials.

MATERIAL	ρ [g/cm ³]	E [GPa]	ν	σ_e [MPa]	σ_r [MPa]
Steel 4140	7.85	20.5	0.29	415	655
Stainless Steel 304	8	20	0.29	215	505
Inconel 718	8.19	20.49	0.284	980	1100
Tungsten	17.75	40	0.28	552	827

Table 1: Mechanical properties for CRFC 3D orthogonal Gonçalves (2008)..

PROPRIEDADE	CRFC 3D orthogonal
Ex [GPa]	31.8
Ey [GPa]	31.8
Ez [GPa]	38.5
Gxy[GPa]	7.8
Gxz[GPa]	5.0
Gyz[GPa]	5.0
ν_{xy}	0.1306
ν_{xz}	0.0670
ν_{yz}	0.0670

The boundary conditions for aerodynamic load (Costa, 2012) (Fig. 8) evaluated for VHA 14-X flying (with no attack angle) at 30km altitude at speed correspondent to Mach number 6.8, as well as the inherent bonds (VHA 14-X coupled to the 2nd stage of the rocket engines) of the structure to each region (and components), which were applied to the VHA 14-X model used for FEM. Additionally, it was inserted the acceleration of 14g's, being 13g's correspondents to the acceleration reached during the atmosphere flight and 1g's to the Earth's gravitational acceleration.

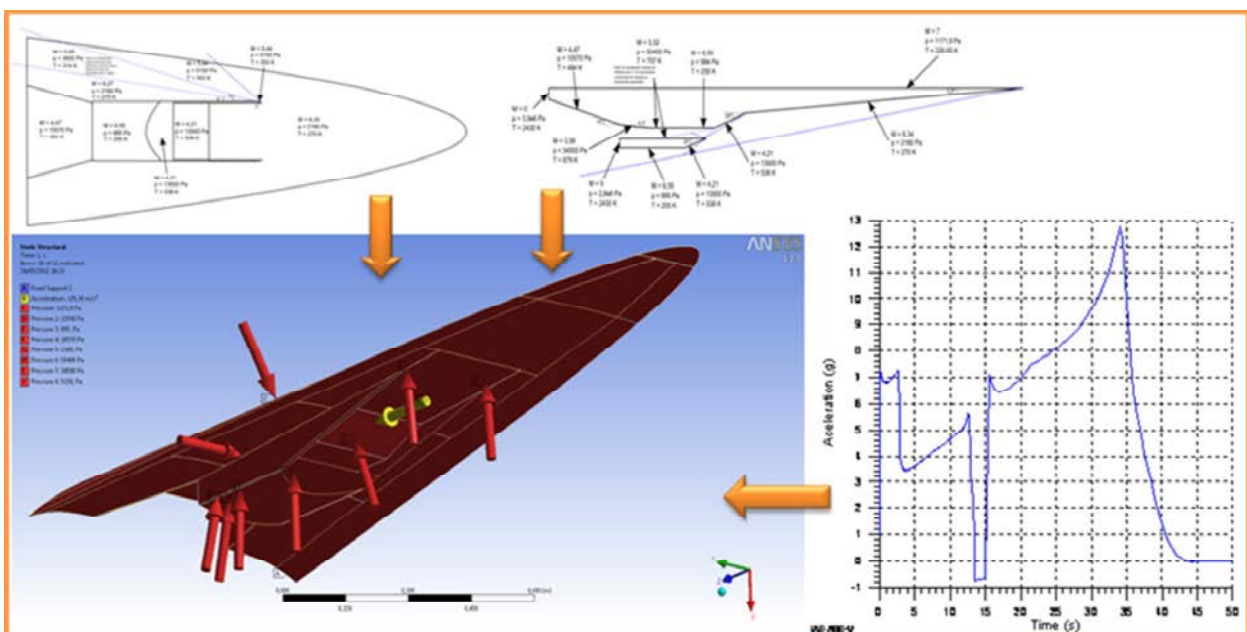


Figure 12: Pressure and acceleration applied to the VHA 14-X.

The equivalent stress σ_e , named as von Mises stress is related to the main stress σ_i , where $i = 1, 2, 3$ (Eq. 1), which used to quantify the ductile material fail model (Shigley et al, 2005).

$$\sigma_e = \left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2} \right]^{1/2} \quad (1)$$

Considering the boundary conditions of the aerodynamic load, acceleration of 14g's and inherent bonds (Fig. 8) as well as the isotropic materials (Table 1) and non-isotropic materials (Table 2) the maximum and minimum equivalent stresses (von Mises) are 65 MPa and $4.8 \cdot 10^{-3}$ MPa at the stringers close to the end (red) and close to the leading-edge (blue) of the upper (Fig. 13) and lower (Fig. 14) surfaces of the VHA 14-X, respectively. Both maximum and minimum equivalent stresses found in the present evaluation are lower than any equivalent stress of the materials (Tab. 1 and 2) used.

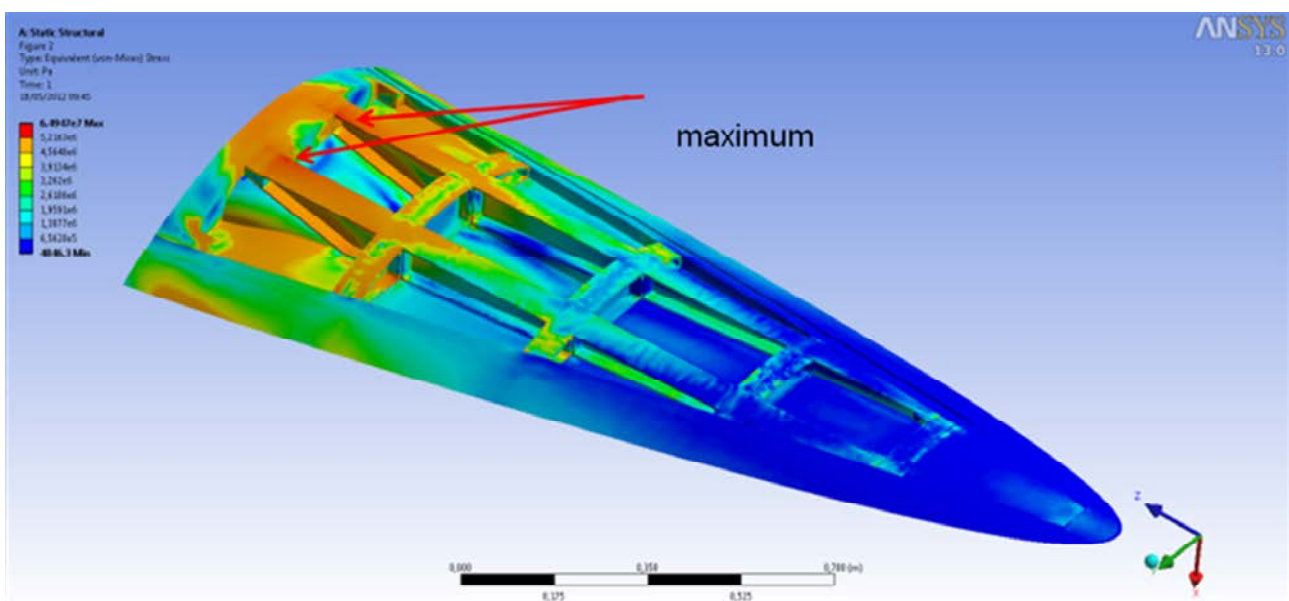


Figure 13: Equivalent stresses (von Mises) fields of the internal structure of the VHA 14-X

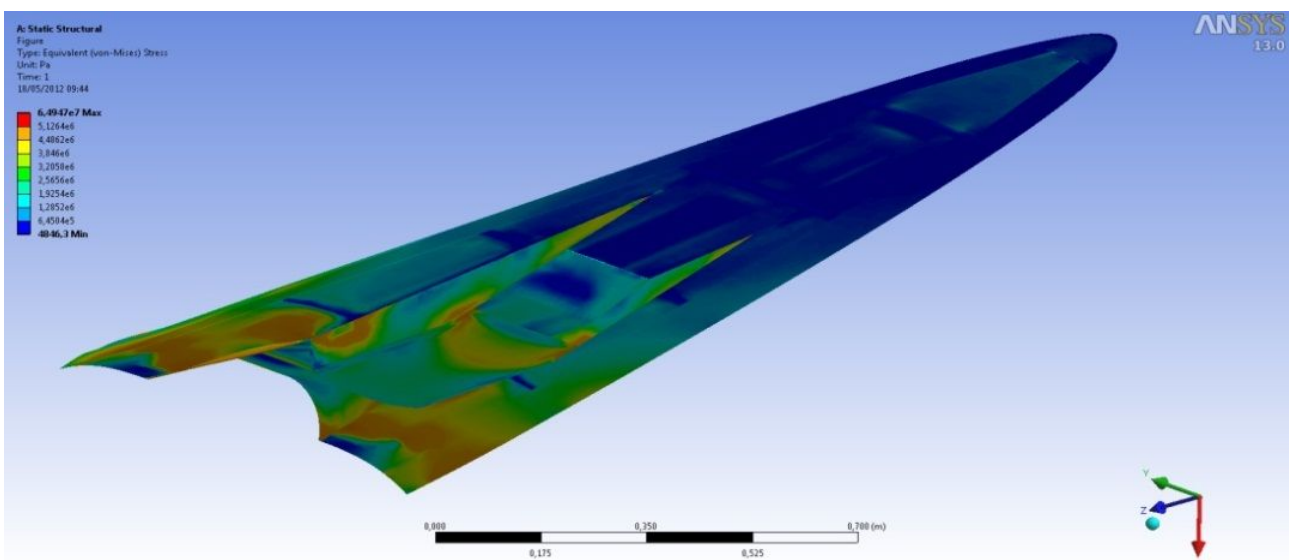


Figure 14: Equivalent stresses (von Mises) fields at the lower surface of the VHA 14-X

Physical deformations can be calculated on and inside a part or an assembly. Fixed supports prevent deformation; locations without a fixed support usually experience deformation relative to the original location. Deformations are calculated relative to the part or assembly world coordinate system.

Figure 15 shows the total deformation is $1.76 \cdot 10^{-3}\text{m}$ and it is occur at the leading-edge of the VHA 14-X, considering the boundary conditions of the aerodynamic load, acceleration of $14g$'s and inherent bonds (Fig. 8) as well as the isotropic materials (Table 1) and non-isotropic materials (Table 2).

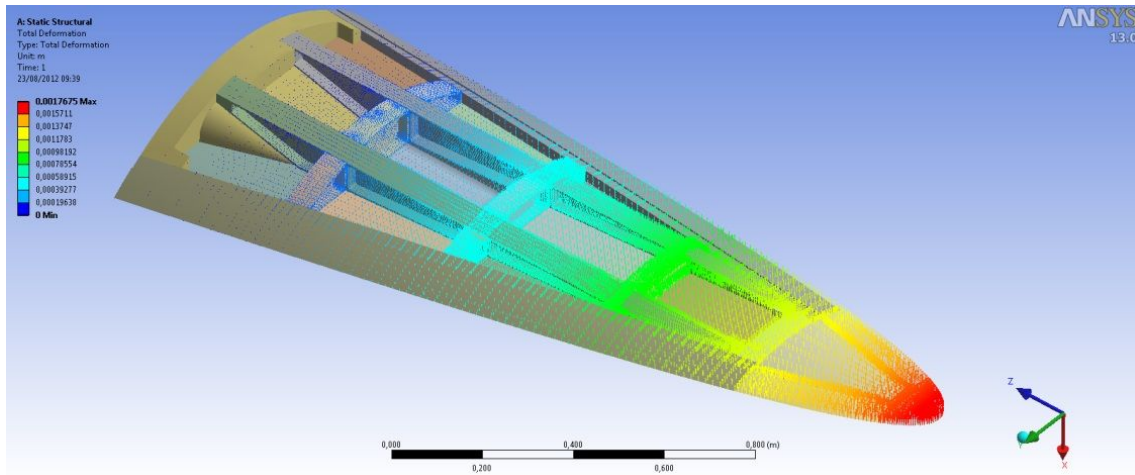


Figure 15: Total deformation at upper surface of the VHA 14-X.

Yet, the X-direction deformation (Fig. 16) reaches the maximum of $1.44 \cdot 10^{-7}\text{m}$ and minimum of $-1.77 \cdot 10^{-3}\text{m}$, while the Y-direction deformation (Fig. 17) is the maximum of $2.68 \cdot 10^{-5}\text{m}$ and minimum of $-2.68 \cdot 10^{-5}\text{m}$. Finally, the Z-direction deformation (Fig. 18) is the maximum of $4.75 \cdot 10^{-5}\text{m}$ and minimum of $-1.12 \cdot 10^{-4}\text{m}$.

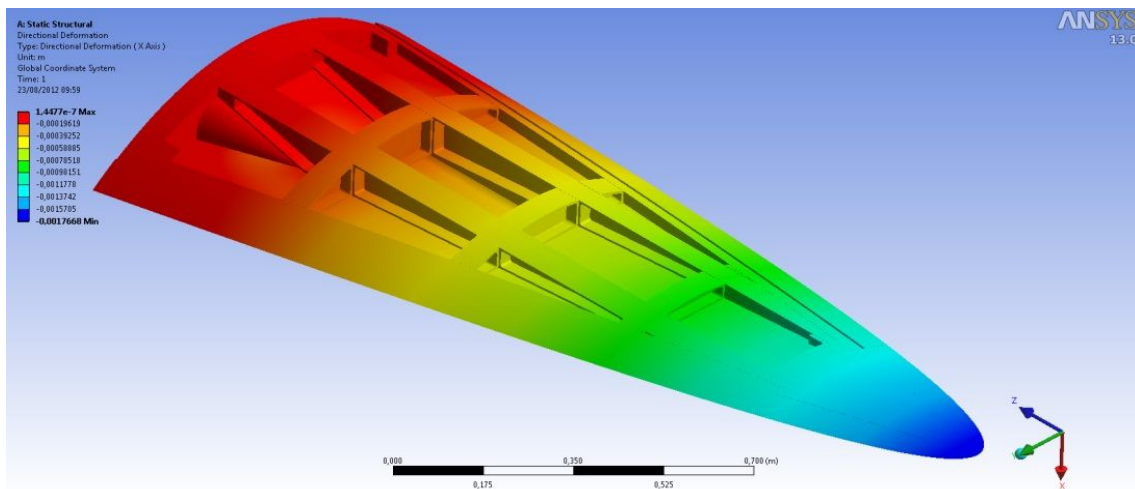


Figure 16: X-direction deformation at upper surface of the VHA 14-X.

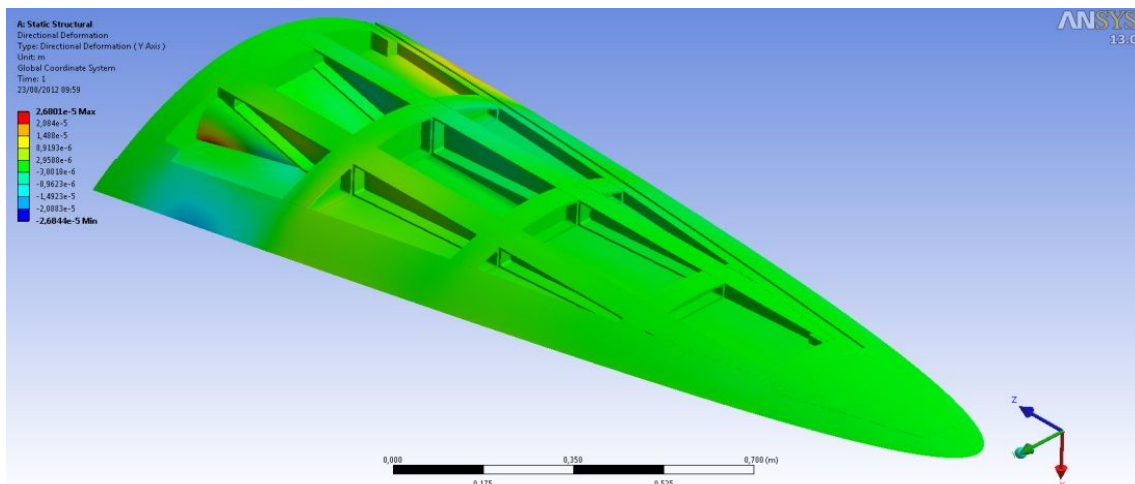


Figure 17: Y-direction deformation at upper surface of the VHA 14-X.

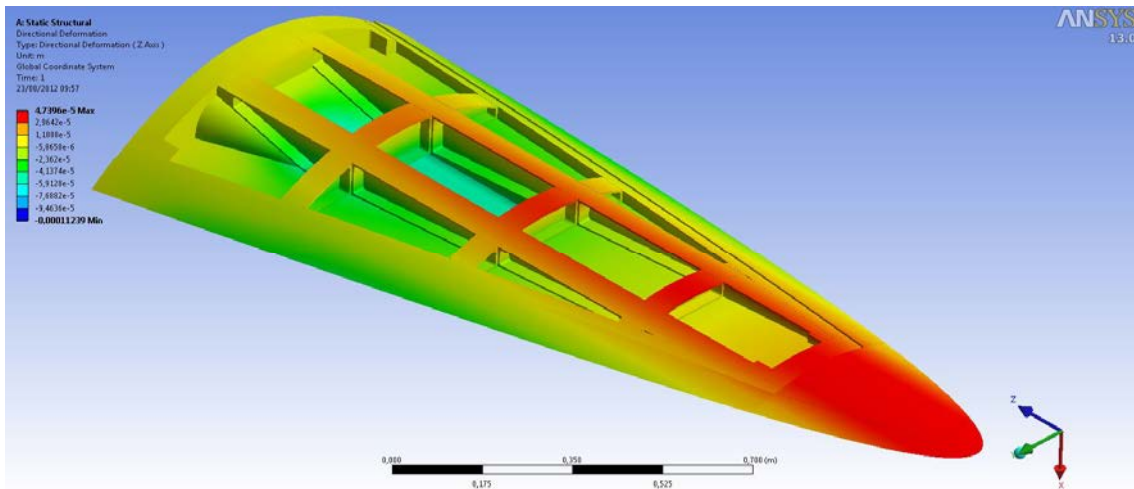


Figure 18: Z-direction deformation at upper surface of the VHA 14-X.

Also, the equivalent deformation, which the origin is from the von Mises theory, may be evaluated by the Eq. 2.

$$\varepsilon_e = \frac{1}{1+\nu} \left(\frac{1}{2} \left[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2 \right] \right)^{1/2} \quad (2)$$

Finally, the principal elastic strain shows the equivalent deformation occur in the elastic region of the used material at the each components of the VHA 14-X. The maximum of $4.8 \cdot 10^{-4}$ m/m and minimum of $-2.5 \cdot 10^{-6}$ m/m (Fig. 19) is found for the principal elastic strain.

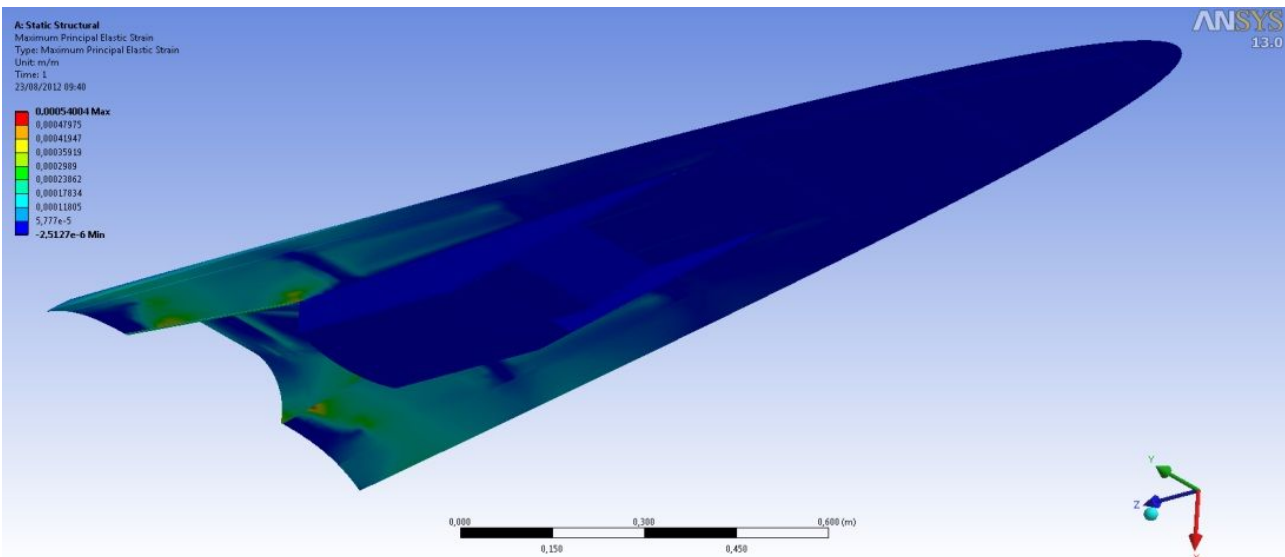


Figure 19: Principal elastic strain at lower surface of the VHA 14-X.

4. CONCLUSION

The primary objective of this work is to present the structural analysis (stress, deformation and elastic strain) using the von Mises theory applied to the VHA 14-X, considering the aerodynamic load, acceleration of 14g's and bonds as well as the isotropic and non-isotropic materials.

VHA 14-X is being designed as an option of a new generation of scientific aerospace vehicle to replace not in a too distant future the conventional multi-stage rocket-powered vehicles, which have flown hypersonically, carrying their own propellant (solid and/or liquid, oxidizer along with fuel) to propel payloads and astronauts to Earth's orbit.

Experimental data as well as analytical theoretical analysis of the waverider and scramjet configurations allowed to obtain the dimensional design of the VHA 14-X. Isotropic and non-isotropic materials were specified using based on the scramjet demonstrators flying at 25-35 km altitude at Mach number 5 to 10 through Earth's atmosphere.

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ANSYS Workbench software, which provides the Structural Numerical Analysis using Finite Element Method, has been applied to the structural analysis of the VHA 14-X waverider unpowered scramjet at 30km altitude at Mach number 7. Preliminary investigations show the maximum stress is lower than the stress of the isotropic and non-isotropic materials used in the structural analysis. Also, total and direction deformations and elastic strain are acceptable for the stress evaluation.

5. ACKNOWLEDGEMENTS

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