THERMO-STRUCTURAL ANALYSIS OF CHAR LAYER IN COMPOSITE ABLATION OF SARA SUB-ORBITAL TPS

Cláudio Gilberto Sauce Bautzer dos Santos, bautzercgsbs@iae.cta.br
Instituto de Aeronáutica e Espaço - IAE, Pç Mal. Eduardo Gomes 50, São José dos Campos, SP, 12228-904, Brazil

Humberto Araujo Machado, humbertoham@iae.cta.br
Instituto de Aeronáutica e Espaço - IAE, Pç Mal. Eduardo Gomes 50, São José dos Campos, SP, 12228-904, Brazil
Faculdade de Tecnologia – FAT/UERJ, Rod. Pres. Dutra km 298, Resende, RJ, 27537-000, Brazil

Abstract. *Space and suborbital vehicles reach high temperatures due the aerodynamic warming, especially in the case of recoverable ones during the atmospheric re-entry. Commonly ablative composites are used as heat shields in the regions near the stagnation point. During the ablation of composites, a char layer is formed in the external surface, which acts as thermal insulator and protects the pyrolysis zone of the atmospheric oxygen that could produce an exothermic reaction, adding heat to the shield instead of reducing it. In this work, the two-dimensional computational simulation of the ablative process in composites used in rocket thermal protection systems via an interface tracking method and a thermo-structural analysis of the resulting char layer is performed, in order to investigate if the integrity of such layer is affected by melting or thermal stresses.*

Keywords*: Composite ablation, TPS, Structural analysis*

1. INTRODUCTION

Along the years ablative materials have been effectively used as TPS (Thermal Protection System) of space vehicles. Such kind of TPS absorbs the heat resulting from aerodynamic heating through the consumption of its own material. If composite materials are employed as ablative TPS, the resulting ablation is a complex phenomenon, related to several physical processes happening simultaneously: phase change (melting or vaporization), pyrolysis and decomposition, char formation, mechanical ablation due the drag and other effects that should be accounted.

The ablation model commonly used for composites considers the existence of three layers in the TPS: the char, the pyrolysis zone and the virgin material. In the first, gases and particles accumulate and diverse processes of flow occur inside and around this layer. The char layer performs an important role in the TPS work, acting as a thermal insulator between the pyrolysis zone and the warmed air outside. Since the pyrolysis is an endothermic reaction and its reaction rate depends on the temperature, it is important to keep this zonE as cold as possible. Another important effect of the char layer is to keep the pyrolysis zone insulated of the external environment, in order to avoid the contact with the oxygen, which could produce an oxidation of the virgin material and the carbonized mass, resulting in an exothermic reaction that may yield additional heat and increase the velocity of the composite consumption.

The char layer consists basically of carbon, and continues to absorb heat until reaching the temperature of oxidation or the temperature of sublimation. This layer can be also removed by aerodynamic forces (drag and shear stresses in the surface) or thermal stresses. In lifting of moderately ballistic reentry, the main thermo-mechanical way of char removing is the oxidation. At temperatures above 3000^{o} C the char sublimates (Torre et al., 1998).

The char layer produced from a polymer normally is weak and fragile, susceptible to fast removing by mechanical action or degradation caused by thermal stresses or increase of the internal pressure. Such behavior reduces the insulation efficiency of the char layer and exposes the internal material to the surface conditions, resulting also in less heat losses by radiation. When the ablative resins are reinforced with fiber, the retained characteristics are improved.

As mentioned, a fundamental function of the char layer is to blockage the oxygen diffusion from the boundary layer to the virgin material, since the endothermic reaction of degradation of the polymeric matrix only occurs in non-oxidizing atmosphere. An excessively recession rate of the protective char layer may result in undesirable exothermic oxidation reaction. At higher temperatures a melt layer can appear, and the char becomes a liquid film over the surface. Normally this layer is removed by the aerodynamic forces (Palaninathan e Bindu, 2005).

In this work, the ablation of a composite TPS is simulated, and a thermos- structural analysis of the resulting char layer is performed for two critical situations. The objective is to check the possibility of melting, oxidation or sublimation of the char layer. The thermal stresses are calculated in order to investigate the effects of thermal conditions over the char layer integrity.

2. PHYSICAL PROBLEM AND MATHEMATICAL MODEL

The sub-orbital platform SARA was initially selected for the studies using the methodology presented in this work. Sub-orbital platforms are low cost alternatives for microgravity research. SARA platform, Fig. 1, is being designed by Institute of Aeronautics and Space – IAE, in Brazil, with such a purpose. Its total mass will be of the order of 250 kg with a payload mass of about 25 kg, and it will provide 6 minutes of micro-gravity environment. SARA may reach speeds of 9300 km/h in atmospheric flight. A future orbital version of SARA may reach an orbit of 300 km and an orbital period of 10 days (Moraes, 1998). Figure 2 shows altitude and velocity maps for SARA.

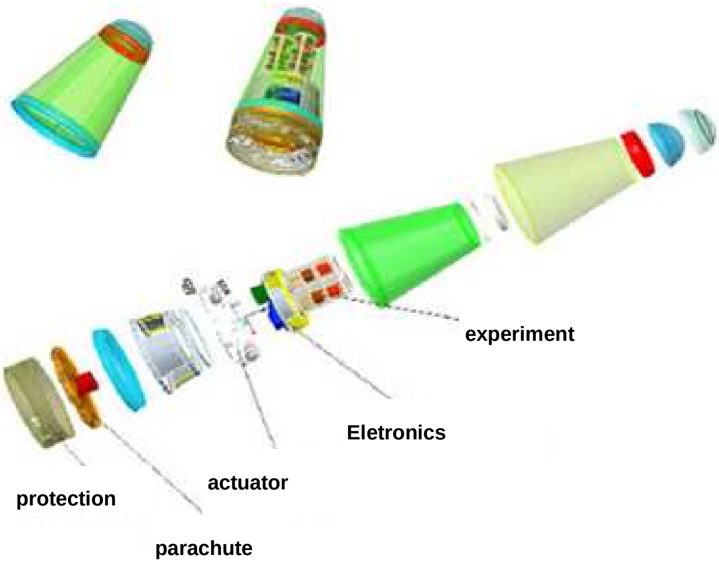


Figure 1. The sub-orbital platform SARA and its inner systems.

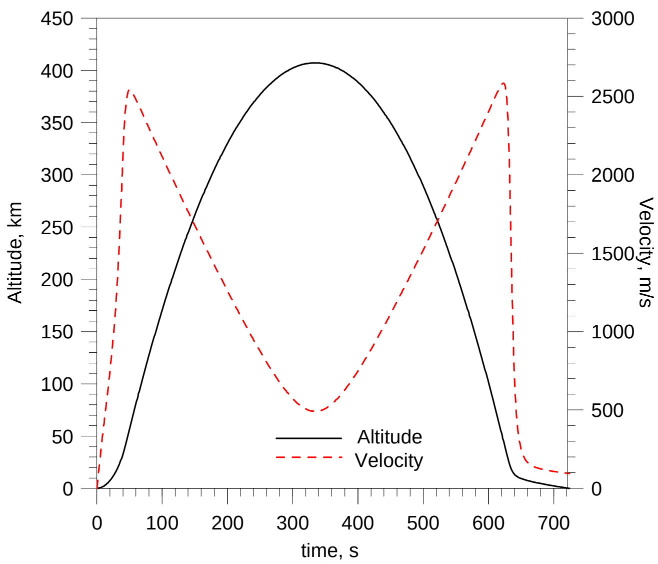


Figure 2. Altitude-Velocity map fo SARA Sub-orbital platform.

2.1. Aerodynamic heating

To predict the heat transfer on SARA, it is necessary to know pressure, temperature and velocity fields around the rocket. That can be accomplished by numerically solving the boundary layer equations. However, such a procedure is expensive and time consuming. In the present work a simpler, but reliable, engineering approach is used. The following simplifying assumptions are made:

- Zero angle of attack;
- SARA rotation around its longitudinal axis is neglected;
- Atmospheric air is considered to behave as a calorically and thermally perfect gas (no chemical reactions).

The free stream conditions ahead of the nose cap are those given by v_∞, T_∞, p_∞, corresponding, respectively, to velocity, temperature and pressure. By knowing v_∞ and altitude, as function of time, together with an atmospheric model [8], it is possible to evaluate the free stream properties. For supersonic flow (M_∞ >1), which begins at 8 s (altitude of 2 km), a detached shock wave appears ahead of the nose. By using the normal shock relationships [9], it is possible to calculate v, T and p after the shock.

The heat flux over the external surface was calculated through the Zoby's method (Zoby et al, 1981). Details of the solution can be found in the work of Machado (2012). The convective heat transfer coefficient is calculated along the y-coordinate that is measured along the body´s surface: y=0 corresponds to the stagnation point, and R is a geometric parameter shown in Fig. 3, were the curved line represents the nose cap surface.

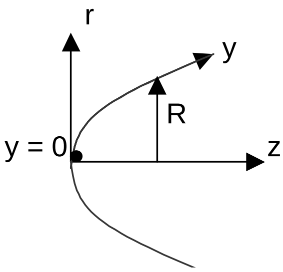


Figure 3. Coordinate system.

It should be pointed out that such a procedure is performed along the payload's surface (following the y-coordinate), for different trajectory times. Therefore, H=H(y,t). The variation of the convective heat transfer coefficient (H) and the recovery temperature (T_{aw} or T_r) at stagnation point are shown in Fig. 4. An energy balance at the surface, accounting the radiative heat transfer, provides the heat absorbed by the wall.

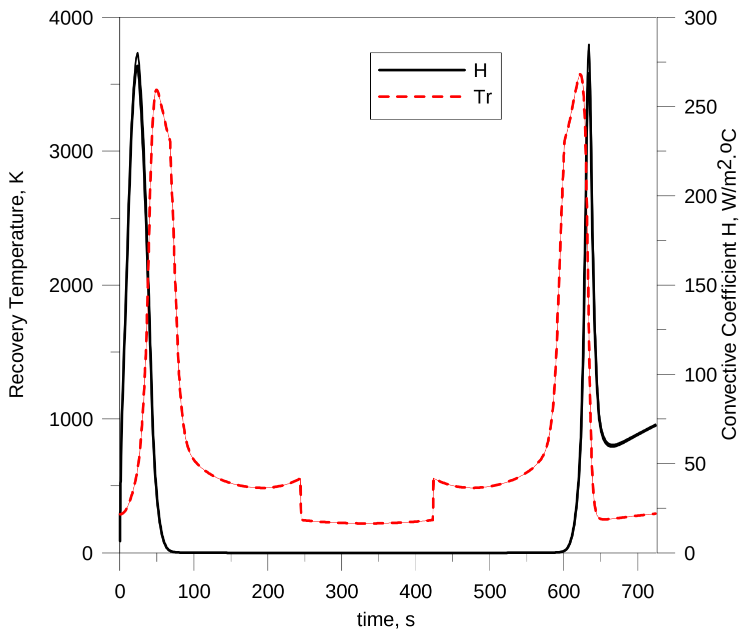


Figure 4. Recovery temperature and convective heat transfer coefficient at stagnation point, during SARA trajectory.

2.2. Heat conduction and ablation

Once the convection heat transfer and the adiabatic wall temperature are known, wall temperature distributions can be obtained. SARA nose cap is covered with a composite material (Si-Phenolic), which works as an ablative TPS. Until the ablation temperature is reached, a transient heat conduction process occurs. Once the TPS surface reaches the ablation temperature, its thickness is reduced; therefore, a transient, coupled conduction moving boundary problem appears.

The set of equations used to represent the physical problem is written according to the interface tracking method (Juric, 1996). The nose cap and the surrounding airflow are represented as parts of a continuous domain of calculation. The application of the energy conservation principle to an infinitesimal volume element in the mathematical domain leads to a partial differential equation for the temperature, namely:

$$\frac{\partial(\rho.C_p.T)}{\partial t} = \nabla(K.\nabla T) + Q \tag{1}$$

where ρ is the density, C_p is the specific heat, T is the Temperature, t is the time, K is the thermal conductivity and Q is a source term that accounts the net heat exchange at the boundary:

$$Q = \int_A q\delta(x - x_F)dA \tag{2}$$

where x is the position in the coordinate system, x_F is the interface position, A is the area, and q is the source term of energy per unit of surface of the interface, and must be adapted to the physical model used to represent the behavior of each interface. The following hypothesis will be assumed to build the mathematical model for the ablative and heat conduction processes in the structure:

- Solid materials are considered isotropic with constant properties.
- The pyrolisis zone is considered a thickless front. Pyrolisis enthalpy and temperature are considered constant.
- The char layer recession occurs through oxidation or sublimation, at constant temperature. The aerodynamic removing of material is neglected.
- Absence of melting layer.
- Full reaction of the gases and perfect mixing with the air in the boundary layer around the external surface, with negligible influence over the air physical properties.
- Air is treated as an ideal gas.
- The flow field around the surface is not affected by the change in the surface geometry and gas injection.
- Radiation is absorbed or emitted for surface, but not transmitted.

All these assumptions have being used in previous works with successfully results in representing the physical process (Machado, 2014; Costa e Silva et al, 2015). The second assumption, in particular, was studied by Sias (2009), which has concluded it was accurate enough, when compared to most complex models for ablation. According to these hypothesis, the heat balance in the external surface yields:

$$q = \rho LV + H(t,y)\left[T_F(t,x_F) - T_{aw}\right] + \varepsilon\sigma\left[T_F^4(t,x_F) - T_{aw}^4\right] \tag{3}$$

where V is the interface velocity, L is the heat of ablation of the char layer, H is the convection heat transfer coefficient and T_F is the interface temperature, ε is the emissivity and σ is the Boltzman constant. One should note that this term might exist in every moving interface. In the pyrolysis front it is simplified, once there is no convection to or from the external flow and the radiative heat transfer is supposed not occur between the layers (since there is no transmission):

$$q = \rho L_p V \tag{4}$$

In this case, L_p is the heat of pyrolysis. The flux of injection gases is also neglected due its low specific mass, when compared to the solid material. It is remarkable that the specific mass that appears in the Eqs.(3,4) is the interface specific mass.

Although the airflow is included in the domain, its effects are implicit in the convection coefficient H. As a consequence, this region is considered adiabatic, and the heat capacity and thermal conductivity are assumed to be null. Once ablation temperature (T_A) is reached, the interface condition becomes:

$$T_F - T_A = 0 \tag{5}$$

A similar jump condition appears in the pyrolysis front (T_p replacing T_A).

2.3 Stress analysis

The Finite Element based ABAQUS® Software (Simulia, 2013) was used to determine the stress and displacement distribution in all layers within the selected region. A small piece of the domain aside the stagnation point was selected for thermal structural analysis. An axisymmetric model built with plate elements was used. The symmetry axis is placed in the left side. The structural boundary conditions and loads assumed were showed in Fig. 5. The degrees of freedom in directions x and y were restricted in the nodes placed at the inferior edge in order to assure the structural stability. The total loading resulted of thermal stresses (temperature gradient) plus aerodynamic loads (total pressure plus shear stress in the surface). A remarkable aspect of stress distribution is the presence of interlaminar stresses acting in the layer interfaces.

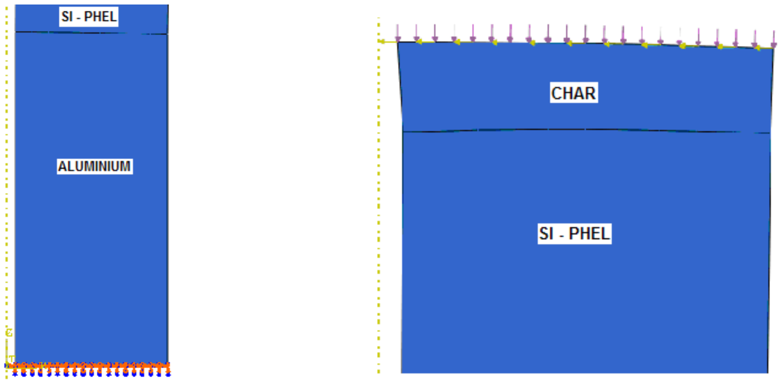


Figure 5. Boundary conditions and loads.

3. METHOD OF SOLUTION

The moving boundary problem was solved by the Interface Tracking Method, introduced by Unverdi & Trygvason (1992), and employed by Juric (1996) in the solution of phase change problems. In this method, a fixed uniform Eulerian grid is generated, where the conservation laws are applied over the complete domain. The interface acts as a Lagragean referential, where a moving grid is applied. The instantaneous placement of the interface occurs through the constant remeshing of the moving grid, and each region of the domain is characterized by the Indicator Function, which identifies the properties of the wall and the air around it. This method allows for the representation of any geometry used in the TPS, and also the characterization of every layer separately. It is accomplished without a high increase in the computational cost and does not need any pre-processing (construction of unstructured grid or coordinate transformation). In this work, this method is employed to estimate the ablative performance of the TPS, considering a two-dimensional approach in both, the heat conduction and the moving boundary problem. Details of the numerical solution are available in the previous work of Machado (2014).

The results were obtained for the region near the stagnation point of SARA, Fig. 6, which corresponds to a circular sector with radius of 280 mm. Note that in that figure Y(capitol)-coordinate has a different meaning of that shown in Fig. 3. Since the flight is considered with zero angle of attack, the problem is considered to be axy-symmetric, and only the half of that region has to be simulated. A 100 x 50 points grid over a domain of 100 mm x 50 mm was employed to simulate the heat transfer and moving boundary problem, with a tolerance of 10-6 for the residual in Eq.(4). A resulting 109 points Lagrangean mesh was obtained for the external interface and a 102 points mesh for the interface between the TPS and aluminium. A previous analysis with less refined meshes was performed, in order to assure that the results reached the convergence. Properties considered for each material are presented in Tab. 1.

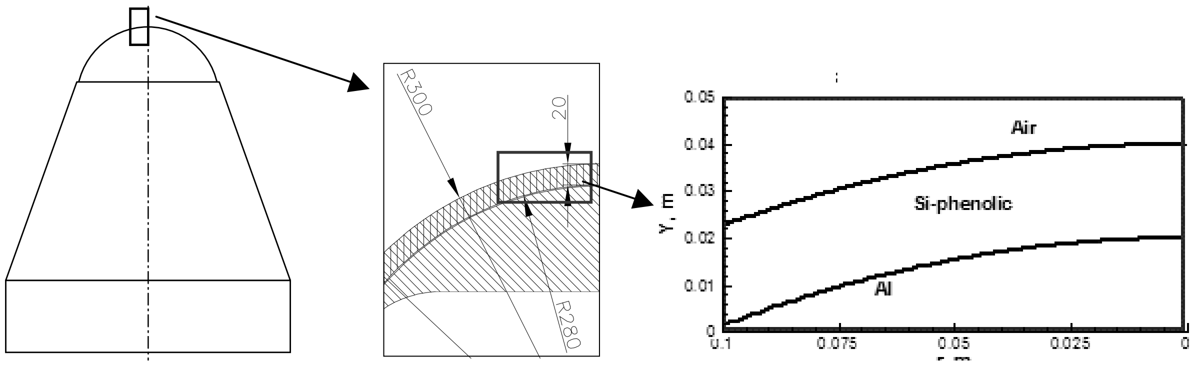


Figure 6. Domain of calculation, layers and dimensions.

Table 1. Properties of materials (Machado, 2014).

Property	**Al**	**Virgin material (Si-Phenolic)**	**Char**
K (W/m^{o}C)	177	0.5213	0.428
Cp (J/kg.^{o}C)	960	1256	879.5
ρ (kg/m^3)	2710	1730	1300
ε	0.06	0.78	0.78
Heat of pyrolysis (MJ/kg)	-	0.214	-
Temperature of pyrolysis (^{o}C)	-	325^o	-
Heat of fusion/sublimation (MJ/kg)	-	-	10.5
Temperature of fusion/sublimation (^{o}C)	-	-	3700^o

4. RESULTS

Results were obtained for two instants: at 44.3 seconds during the ascendant period and at 631.1 seconds during the reentry, were the maximum thermal loads happened. The thermal and mechanical loads considered were the pressure in the external surface which was extracted from the results of Zoby's Method and the shear stresses which were obtained from the Newton's Law of viscosity. Fig. 7 shows the interfaces and the loads at these two instants. In these cases there is no melting of the char layer, since the peak temperatures are both bellow the assumed char melting temperature.

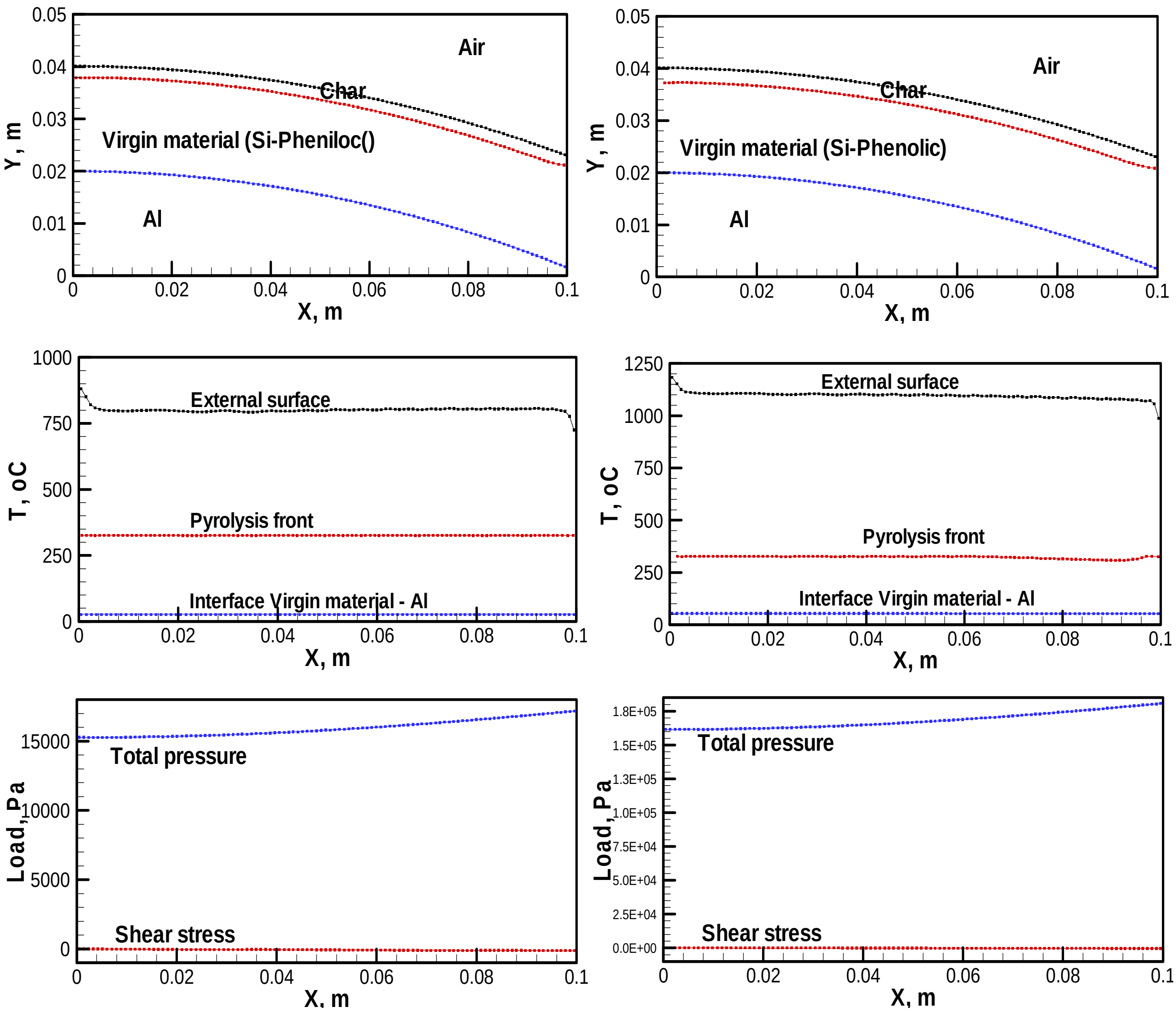
The Finite Element mesh and respective temperature distributions for both cases are shown in Fig. 8. The higher temperature gradients can be observed in the char region, what attests this important effect as a thermal insulator. Figure 9 shows the Von Mises Stress distributions and Fig. 10 shows the respective displacements. The major stresses occur in the base, made of aluminium, as a consequence of the imposed boundary condition in that region. The displacements are quite small and; the major values occuring in the char layers due both, thermal and structural loads. The displacements in the regions near interfaces are consequence of the stress variation in these regions.

Table 2 presents a comparison among the maximum values of the stress reached in the char region and the shear limits according with temperature for the char, estimated by Silva (2015) for burned samples of the same composite. The stresses in the char layers for both cases are far below the limits, which indicate that in this case the char layer would keep the integrity during the whole flight period. Although this direct comparison among the numerical results and the experimental results extracted from literature is not possible, since the first are Von Mises stresses and the second accounts the anisotropy of the burned composite, the difference of order justifies that conclusion.

It is remarkable that some physical effects that could affect the char layer integrity like the pyrolysis gas flow were not considered in the structural analysis, since it was not accounted explicitly in the ablation model. The fact that SARA performs a sub-orbital flight results in low thermal and pressure loads during reentry. Results shall be quite higher for orbital or planetary reentries.

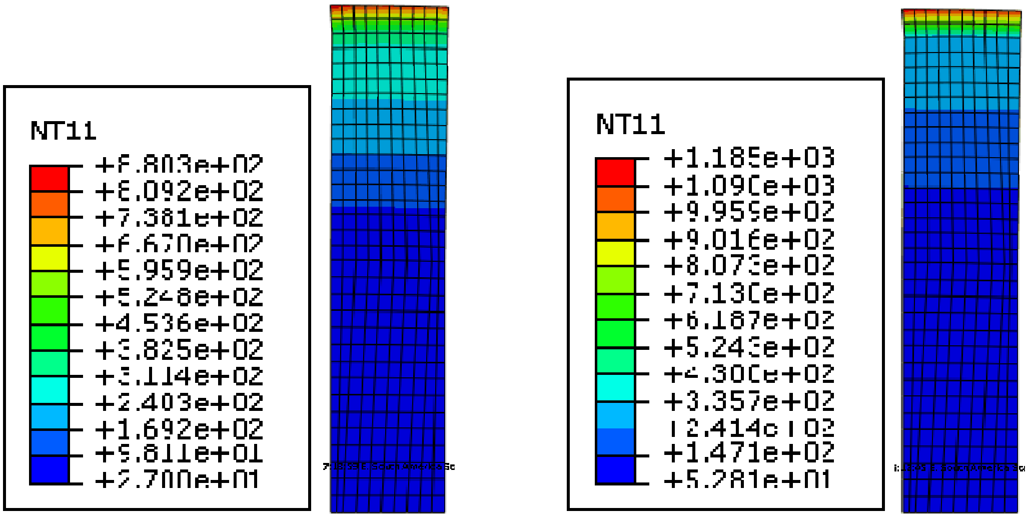
Table 2. Comparison among numerical results and literature data.

Time	**Von Mises Stress**	**Shear limits (Silva, 2015)**
44.3 s	0.10 MPa	18.87 MPa (880^o C)
631.1 s	0.154 MPa	4.05 MPa (1,181^o C)



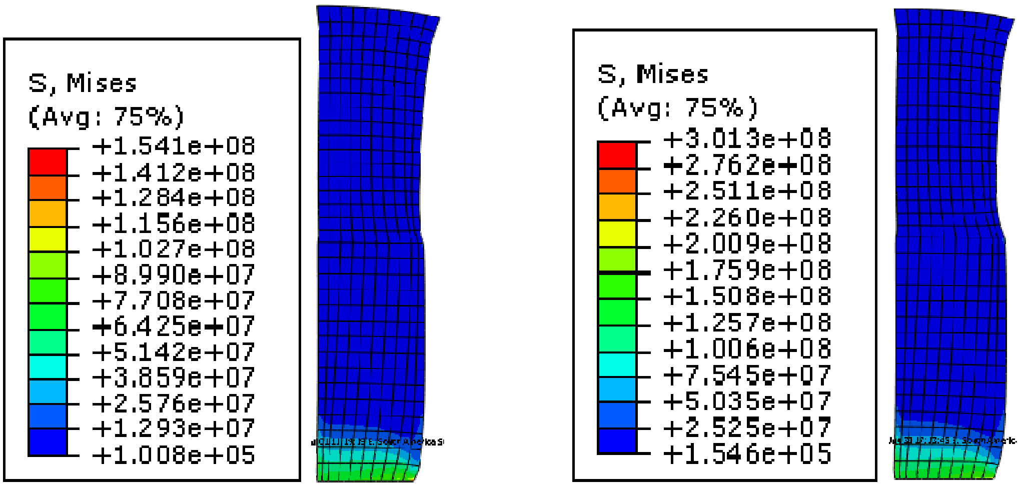
(a) 44.3 seconds *(b) 631.1 seconds*

Figure 7. Interface shapes, thermal loads in every interface and pressure loads over external surface.



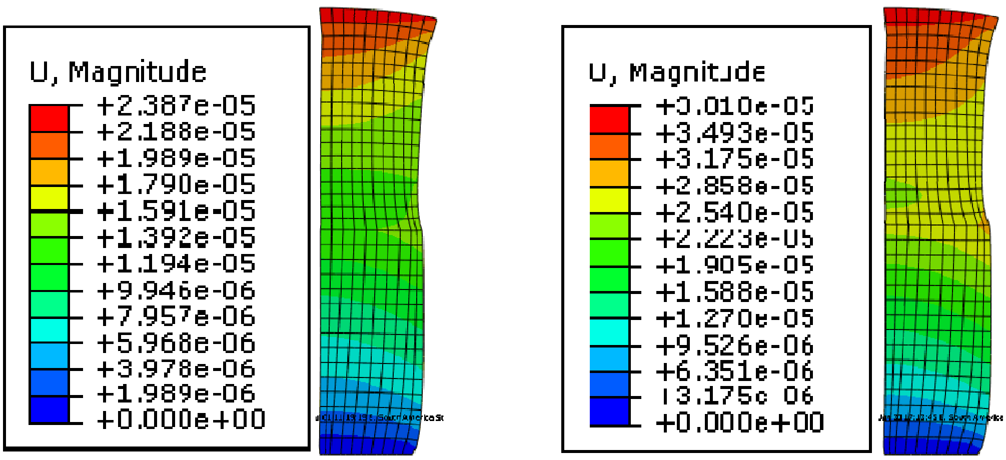
(a) 44.3 seconds *(b) 631.1 seconds*

Figure 8. Finite element models and temperature distributions in °C.



(a) 44.3 seconds *(b) 631.1 seconds*

Figure 9. Von Mises stress distribution, Pa.



(a) 44.3 seconds *(b) 631.1 seconds*

Figure 10. Displacements in scale, m.

5. CONCLUSION

In this work, the two-dimensional computational simulation of the ablative process in a Silica-Phenolic composite was performed via an interface tracking method. The char layer formation after the pyrolysis of the virgin material in the TPS of the SARA Sub-orbital platform was simulated and two cases corresponding of the peak temperatures in the ascendant and re-entry periods were selected for study. A thermo-structural analysis using a Finite Element commercial code was also performed, in order to estimate the stresses acting over a small section of the domain close to the stagnation point.

According with the results, the maximum temperatures are not high enough to melt the char layer and the stresses are far bellow the limits considered for such material. These were preliminary results for a sub-orbital recoverable vehicle. Different results would be obtained for more dramatic flight conditions, like orbital flight or planetary re-entry.

6. REFERENCES

Costa e Silva, S. F., Machado, H. A. e Bittencourt, E., 2015, “Effect of the Fiber Orientation Relatively to
the Plasma Flow Direction in the Ablation Process of a Carbon-Phenolic Composite”, J. Aerosp. Technol. Manag., Vol.7, No 1, pp.43-52.

Juric, D., 1996, “Computations of Phase Change”, PhD. Thesis, University of Michigan.

Kumar, R. R., Vinod, G., Renjith, S., Rajeev, G., Jana, M. K. and Harikrishnan, R., 2005, “Thermo-structural analysis of composite structures”, Materials Science and Engineering, A 412, pp 66-70.

Machado, H. A., 2012, “Two-dimensional simulation of ablation due to aerodynamic heating in the SARA sub-obital platform”, High Temperatures-High Pressures, Vol. 41, pp. 255–271.

Machado, H. A., 2014, “Simulation of Two Moving Fronts Ablation in a Composite Thermal Protection System Via an Interface Tracking Method”, 11th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, Atlanta, GE.

Moraes Jr., P., 1998, “Design Aspects of the Recoverable Orbital Platform SARA”, Proceedings of 8th Chilean Congress of Mechanical Engineering, Concepcíon, Chile.

Palaninathan, R. and Bindu, S., 2005, “Modeling of Mechanical Ablation in Thermal Protection Systems”, J. Spacecraft and Rockets, Vol. 42, No. 6, pp 971-979.

Schneider P. J., Dolton, T. A. and Reed, G. W., 1968, “Mechanical erosion in charring ablators in ground-tet and re-entry environments”, vol. 6, no.1, pp 64-72.

Sias, D. F., 2009, “Hybrid Solutions for Heat Transfer on Ablative Thermal Protection Systems”, M.Sc. Dissertation, Federal University of Rio de Janeiro - UFRJ, Rio de Janeiro, Brazil (in Portuguese).

Silva, H. P., 2015, “Mechanical Characterization through Shear in Carbon-Phenolic Composite Materials for Aerospace Applications Submitted to High Temperatures”, M.Sc. Dissertation, University of Campinas - UNICAMP, Campinas, Brazil (in Portuguese).

Simulia, 2013. “Abaqus 6.13 Online Documentation”, Dassault Systémes, Providence, RI, USA. <http://50.16.176.52/v6.13/>.

Torre, L., Kenny, J. M. and Maffezzoli, A. M., 1998, “Degradation Behaviour of a Composite Material for Thermal Protection Systems, Part I – Experimental characterization”, J. Materials Science, 33, pp. 3137-3143.

Unverdi, S. O. and Tryggvason, G., 1992, “A Front-Tracking Method for Viscous, Incompressible, Multi-fluid Flows”, Journal of Computational Physics, v. 100, pp. 25-37.

Zoby, E. V., Moss, J. N. and Sutton, K., 1981, ‘Approximate Convective Heat Equations in Hypersonic Flows”, Journal of Spacecraft and Rockets, Vol. 18, No. 1, pp. 64-70

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