Variable Curvature Thermal Protection Structures for Re-entry Vehicles

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ABSTRACT

A smart thermal protection system is a new concept of adaptive structure conceived to work in a harsh environment as the atmospheric re-entry. Such a concept is proposed for morphing the leading edges or the nose of a space transportation system through the modification of its geometry during flight.

The design process to achieve the optimal solution start with a selection of different concept design drafting the working principle of mechanisms able to displace the structure from one geometry to the other. The project has been developed in several phases with an increasing level of detail. Two concepts have been promoted for a full design analysis and presented in this paper. The analysis concern the study of the kinematisms with multibody codes in order to test the effectiveness of the actuating mechanism. The level of deformation assumed by all the element of the TPS and the relevant structure has been checked to verify the possible failure and the consequent structural damage of the TPS.

Moreover the analytical assessment includes an effective material research and thermal and thermo-mechanical calculations. The FEM analysis is performed to reach the complete refinement of the mechanism and the results are compared with existing benchmark solutions.

1. INTRODUCTION

The first studies of adaptive structures in aeronautics are quite recent, dated about ten years. The research programs in this field investigated the possibility to adapt the shape of an airfoil by mean of piezoelectric materials in order to reduce aeroelastic instability phaenomena. Many others experiments with the aim of control the aerodynamics of the wing by morphing its shape was conducted during the years with different configurations of actuators and materials.

In the contest of re-entry vehicles or reusable space transportation systems, the adaptivity is made more challenging due to the extreme flight conditions that are present at least in some phases of the mission. The debate on the possible development of reusable space transportation systems and of re-entry vehicles has given the impulse to the studies on a new generation of advanced thermal protection systems that in perspective could optimally combine performances at different mission phases [1] [2]. In principle different geometries give the best conditions for different flight phases: a sharp geometry for ascentional paths, hypersonic flights and landing, a blunt geometry for re-entry phases.

The idea to have a “smart” system aims at getting the best performance of the state of the art materials and technologies by introducing the concept of morphing.

Morphing the wing profile shape is a research topic in aircraft development which progresses steadily. The common element to several projects of this type is the flexibility, or compliance, of all or a part of the structure under the action of the mechanism that controls the shape. The skin of these structures are made with lightweight materials with clear elastic properties. Unfortunately this concept of "compliance" match very badly the field of the high-temperature thermal protection, as i.e. for the atmospheric re-entry. The variety of materials for this kind of applications is extremely reduced so far and comprehends ceramics type materials, for the great majority of the cases. For their nature, ceramics are characterized by an extremely high stiffness to the detriment of the flexibility required for the morphing. Moreover the mechanism responsible for the morphing has also to withstand the harsh environment of the re-entry phase.

The research project on variable curvature concepts for smart thermal protection systems (Smart TPS) aims at finding a possible solution to the trade-off between these two needs.

2. PRELIMINARY DESIGN PHASE: THE BRAINSTORMING

The absolute novelty of the project did not obliged to follow any specific line of development. The concept of Smart TPS can be studied an applied to any part or component of a vehicles such to improve advantages in relation with a pre-existing configuration.

In order to gather and explore Smart TPS ideas in a systematic way it is useful to first identify potential application areas on typical launch and re-entry vehicles together with the relevant flight environment. In this context several ideas have been elaborated in different detail to be applied in leading edges, noses, body-flaps and air intakes.

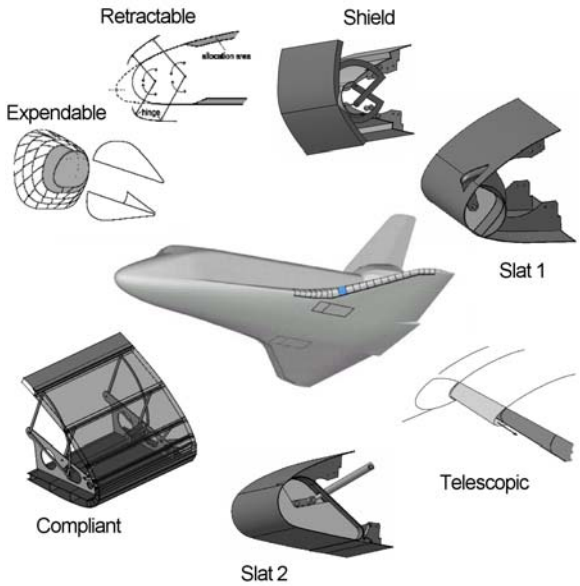

Figure 1. Collection of Smart TPS ideas for variable geometry.

The basic flight performance advantage offered by the proposed ideas was a reduction of the drag during ascent phases while maintaining the drag during re-entry. Some of the concepts even offered to adjust the drag again during the final approach and landing phase. A short list of the most interesting ideas follows:

- Telescopic: a sharp leading edge stored inside the fuselage and mechanically over placed on the blunt one by a sliding movement.
- Retractable: a sharp leading edge retracted and placed in an allocation area.
- Shield: a heat resistant shield retractable.
- Expandable: a sharp profile to be used in ascent phase and detached before re-entry phase.
- Compliant and Slat: follow more in detail

In order to evaluate the expected benefits of proposed Smart TPS ideas and in view of the development level, vehicle types benchmark constructions have been selected with the relative environmental flight loads [3]. Each Smart TPS idea was drafted against these reference loads and compared with the benchmark construction. As soon as a significant drawback of the idea became evident during drafting and could not be overcome by the team further exploration of the idea was stopped.

The screening of potential ideas brought to the selection of two of them to be applied to a leading edge; the Shuttle Orbiter was considered as reference benchmark. We named one “Slat mechanism” and “Compliant mechanism” the other [5] [6].

3. THE REINFORCED THERMAL PROTECTION

The leading edge of the Shuttle Orbiter is basically composed in a sequence of blocks connected each other and clamped to the wing box. Each block is a shell in C/SiC [7] [8], 6mm thick, reinforced by two ribs that provide also the clamping point. In order to introduce a kinematism that allows to morph the shape (curvature) of it, a new design of the TPS, specific for this purpose, needs to be considered. When the shell has to be modified to locate a mechanism, each cut on it involves the introduction of a reinforcement into the structure. The new technologies of C/SiC manufacturing enable the production of pieces geometrically more complex as a unique bloc composed of reinforcements and shell. Providing the structure of reinforcements allows to reduce the thickness of the shell and preserve the stiffness without increase sensitively the overall weight.

The presence of a mechanism into the leading edge enclosure limits strongly the maximum temperature allowable into the same enclosure. It is necessary provide the thermal protection of a good and light insulation, as the Saffil material, to stop as much as possible the thermal heating to the interior. A further barrier composed of a thin C/SiC shell covered with a low emissivity coating can be applied as inner shield. This concept of TPS (fig. 2), designed as a multicell structure, offers more possibility to apply a mechanism for the geometry morphing.

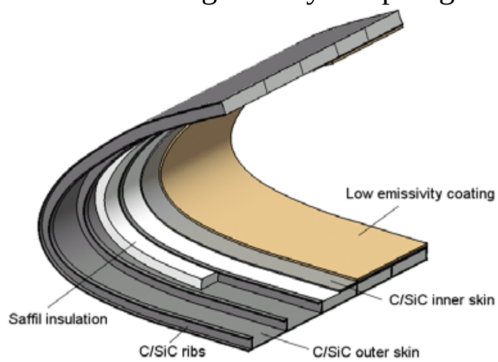

Figure 2. Multicell thermal protection structure.

4. THE SLAT MECHANISM

The first concept ideated to produce a change in geometry of the leading edge consists of switching between two edges with different curvature. This function is demanded to a rotating head [3], opportunely shaped, that replaces the windward part of the airfoil. The possible ranges for the curvature changes are limited by the dimensions of the rotating head in relation with the dimensions of the wing (fig. 4). It is possible to apply this concept to the Shuttle’s wings providing a 160 mm radius for the blunt configuration and a 70 mm radius for the sharp one.

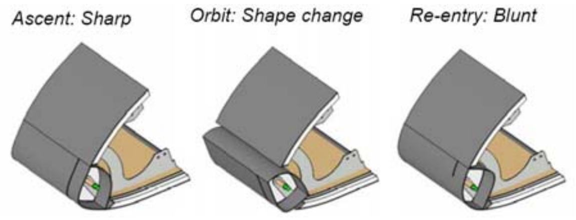

Figure 3. Morphing leading edge curvature by a slat mechanism.

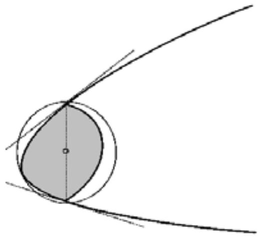

Figure 4. Geometry of the rotating head.

The actuation of the slat mechanism is provided by a stepping motor that transmits a rotation of 180° to the head through a shaft. Several motors can be distributed along the wing leading edge, one for each section, in order to guarantee the redundancy, or just one located in the fuselage, where is less exposed to the heating of the re-entry phase. The coupling and the sealing between the leading edge segments is the most critical part and depends strongly on the shape of the wing.

The protection to the heating for the rotating head has the same bases of the TPS seen and is shown more in detail in figure 5. The external layer is made in C/SiC, 2mm thick. His structure, as a pipe, has a high bending stiffness. Ribs, opportunely inserted into the pipe, provide both a further stiffening of the structure and the transmission of the rotation from the shaft. The supports of the shaft are the most sensitive component of the system and it need to be located in a protected area. All the space between the outer skin in C/SiC and the shaft is insulated by the Saffil material. For all the rest of the leading edge is available as we said about the TPS multicell concept.

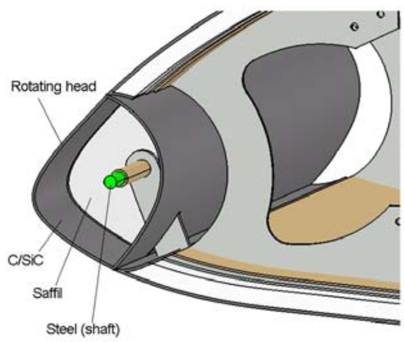

Figure 5. Detail of rotating head and material selection.

Preliminarily, a mass penalty of 10 kg to 15 kg per leading edge unit has been estimated for this concept which has to be evaluated against vehicle weight benefit (fuel saving and tank mass saving). It is obvious that any favourable mass saving balance is related to increasing atmospheric flight period during ascent.

Favourably the slat mechanism provides some protection of the vehicle against leading edge damage. In other terms this mechanism presents an advantage in terms of safety. During launch, ascent path or orbiting phase, the blunt profile, the integrity of which is fundamental for the re-entry, is stored in a protected position. If the sharp profile is damaged, the option that the blunt profile is safe exists and then the re-entry become possible.

5. THE COMPLIANT MECHANISM

The compliant mechanism basic features are depicted in figure 6. The leading edge shape is approximated by series of connected, rigid and thin blades fabricated in high temperature resistant C/SiC materials (see figure 7). In contrast to the slat mechanism this concept is designed to morph the leading edge continuously from a shape to the other. The procedure of switching for the slat mechanism is executed in orbital flight; instead through the compliant mechanism it is possible to control the shape also during atmospheric flight because the morphing is progressive. The approaching and landing flight phases with a more aerodynamic surfaces can be achieved.

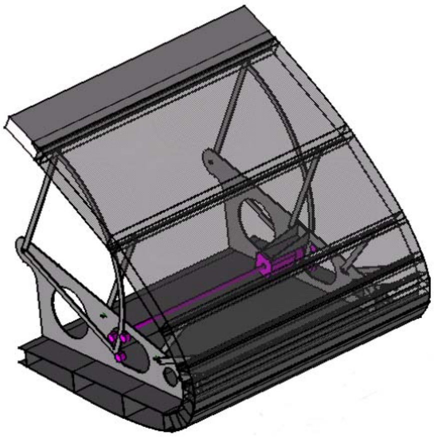

Figure 6. Compliant mechanism.

The basic principia of this mechanism is his capacity to transfer the action of a single force to several points on the leading edge surface by a single degree of freedom kinematism [10] [11]. The mechanism is actuated by a simple rotation of one of the C/SiC arms around his pivot placed on a fixed C/SiC rib. The mechanism, built as a series of arms, moves forward the upper skin of the leading edge and rotates the frontal plates at the same time to make a sharp shape (figure 8). Choosing the farthest distance of the arm to the stagnation point a rather small rotation of 3.5° is fully sufficient to modify the curvature radius from 160 mm to 40 mm.

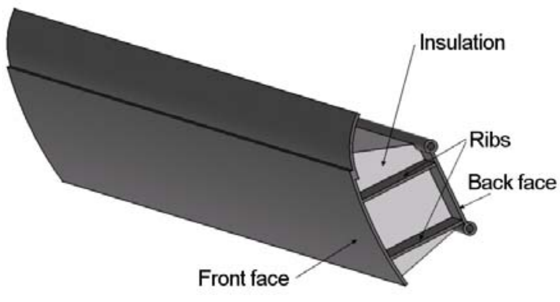

Figure 7. Sketch of a blade.

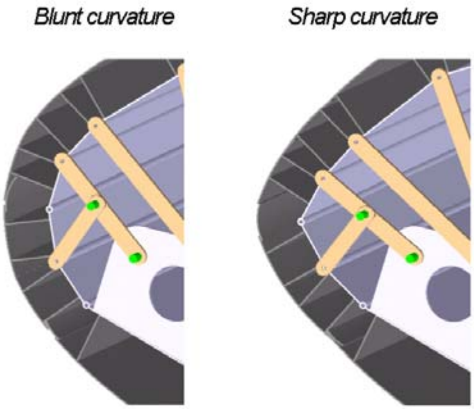

Figure 8. Detail of the compliant mechanism near the stagnation line.

Within and between the blades high temperature insulation is located witch lowers the temperature of the blades back face skin. This insulation between the blades provides the sealing function in combination with overlapping C/SiC lips. The total weight of a leading edge unit including the stepper motor and the power provision is 29.8 kg, i.e. slightly below the one of the benchmark.

A multibody analysis was performed to compute the torque necessary to win the system of force and torques generated by the pressure field around the wing at the instant of maximum intensity. The actuator has to keep in equilibrium the whole system with a torque of 1250 Nm for each meter of wingspan for the blunt configuration and with a torque of 400 Nm for the sharp one (figure 9). These values does not take in account the loss for friction, too complex to be estimated without a direct experimentation.

It is possible to realize a unique actuator for all the wing, but the torque acting on the shaft results very high and the shaft has to be sized in big dimensions. It is preferable to insert an smaller actuator in each segment.

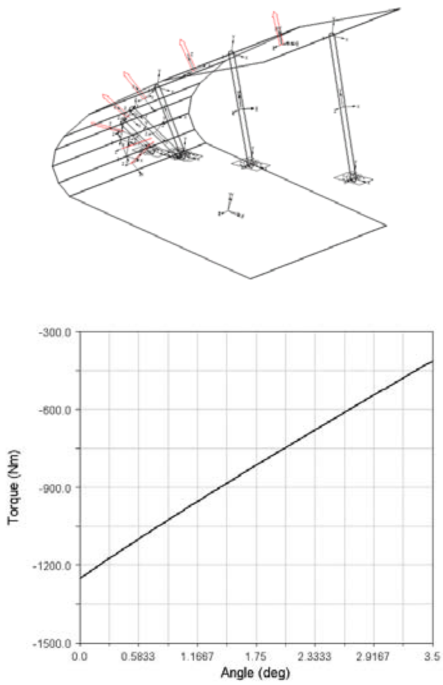

Figure 9. Multibody model and actuation graph (torque vs. angle).

The requested rotation of the arm can be produced by a electric stepping motor, acting through a reduction gear system. If we consider a commercial product (produced by Phytron

Elektronik GmbH [12]), the specifications are complied by the model VSS 52 with the planetary gear system VGPL 52 to reduce the speed and increase the torque. From the specification of the gear we can apply a max torque of 30Nm: to reach 1250Nm we need a further reduction system with a ratio of 42:1 as illustrated in figure 10.

VSS52 is a stepping motor working under extreme environmental conditions: high shock and vibration, temperatures range -270°C to +300°C, vacuum to 10^{-11} Torr, radiation hardened to 10^{8} Rad. VGPL52 is a planetary gear system fitting to the VSS52.

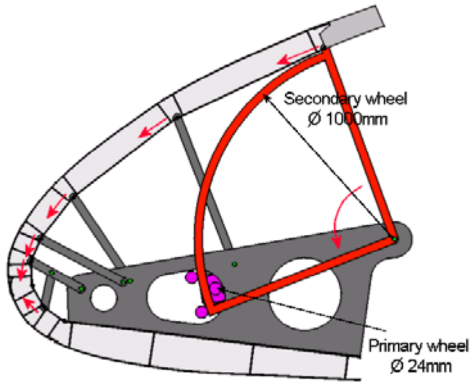

Figure 10. Kinematism of the compliant mechanism.

In order to protect to the harsh environment of the enclosure, the motor is encapsulated in a C/SiC box filled by Saffil insulation, if needed protected with an heat sink layer, and clamped to the upper bound of a rib. The clamping is as far as possible from the back face of the lower blade to interpose the maximum thermal resistance in terms of conductivity. Moreover to protect the inner mechanism from the excessive heating, in particular from the radiation heating inside the enclosure, it is necessary to provide the back faces of the blades by a coating with a low emissivity coefficient (the C/SiC has one too high =0.85). In particular it needs to reduce as possible the heating comes from the lower blades and direct to the ribs and the motor. These parts have to be protected also from the conduction heating of the air inside the enclosure. For this reason the ribs can be provided by a cover in saffil.

6. HEATING-COOLING CICLE: THERMO-MECHANICAL LOADS

The technical requirements [4] [13] for the TPS depend on the re-entry and ascent trajectory chosen for a particular vehicle. The highest heating levels are to be expected for small re-entry vehicles with high wing-loading and for air-breathing launch vehicles during ascent. For these vehicles the surface temperature may locally exceed 1650 °C. Such temperature levels combined with a low ambient pressure may severely decrease the safe lifetime of components and materials. For the thermal loads always the maximum loads, i.e. the re-entry values, if applicable, have been taken into account.

The maximum stagnation point heat flux of the Shuttle Orbiter is in the order of 500 kW/m² during re-entry. However, in the leading edge units 7 to 10 on each wing, the maximum heating rates approach levels of about 600 kW/m². The time period for which the heat flux is not below 50% of the maximum value is about 15 minutes. Re-entry heating duration peak levels are defined to last 5 minutes. Peak heating level is preceded and trailed by a ramp of 10 minutes in which the fluxes are linearly rising from / decreasing to zero (fig. 11).

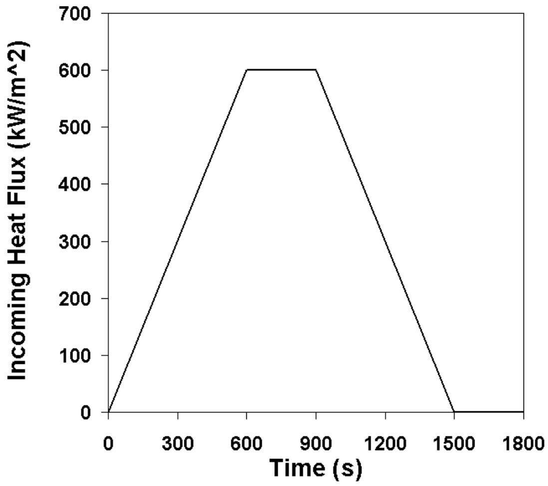

Figure 11. Specified re-entry heating timeline.

The specified re-entry heating timeline is relative to the stagnation point of the leading edge. For the adjacent regions the heat flux is scaled with a function of the streamwise distance (fig. 12). The radiative heat flux for the external surface is evaluated considering the presence of a coating treatment with an emissivity coefficient of 0.85.

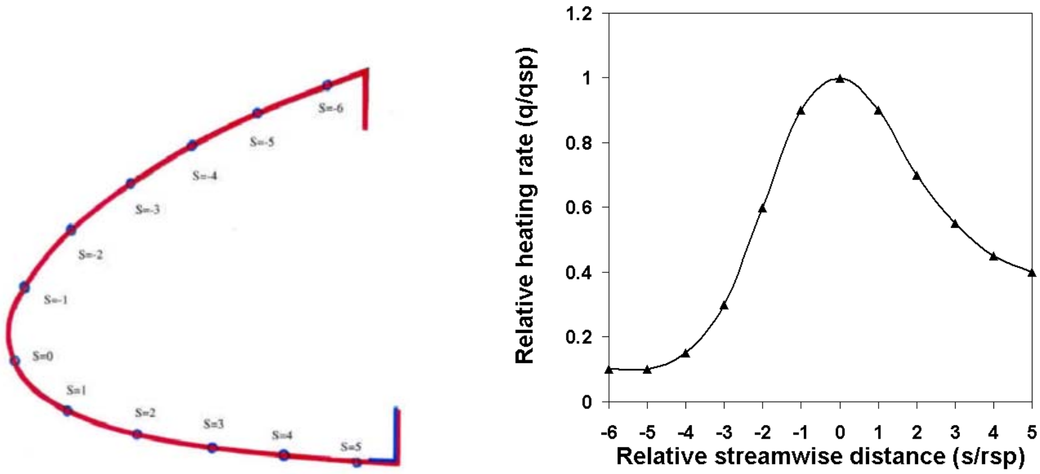

Figure 12. Specified re-entry heating profile at stations

Differential pressure between windward and leeward side of the leading edge are assumed not to exceed 30 kPa. To this differential pressure the overpressure on the windward side shall contribute 25% whereas the underpressure on the leeward side shall be 75%. The transition between overpressure and underpressure regime shall be at the stagnation point (s=0). It shall be assumed that for a streamline on the leading edge the overpressure reaches linearly its maximum level of 7.5 kPa within a distance of (about) one curvature radius from the stagnation point (s=1) and remains afterwards contant. Similarly, along the streamline on the underpressure side the final value of 22.5 kPa shall be reached at s=-1 (fig. 13).

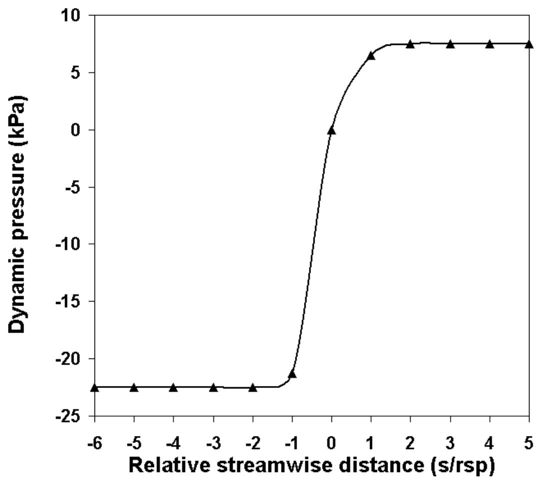

Figure 13. Specified differential pressure profile at stations.

7. THE NUMERICAL TESTS

Four kind of analysis are performed to put in evidence the different effects of the loads and their superposition. The main analysis information is resumed in table 1. The thermal load follows a complete heating/cooling cycle to take in account the effect of thermal inertia. The mechanical load is applied in conservative way by the maximum dynamic pressure field reached during re-entry phase. Both the loads are referred to the benchmark case specified in ref. [4].

Main analysis information

Field	Loads	Analysis type	
Mechanical	Dynamic pressure	non-linear (large displacements)	steady-state
Thermal	Heat flux	non-linear (boundary radiation, material properties temperature dependent)	dynamic transient
Coupled	Heat flux + thermal expansion	non-linear (large displacements, boundary radiation, material properties temperature dependent)	dynamic transient
Coupled	Dynamic pressure + Heat flux + thermal expansion	non-linear (large displacements, boundary radiation, material properties temperature dependent)	dynamic transient

Table 1. FEM main analysis information.

For the slat mechanism, the finite elements analysis are limited to the component part more stressed: the rotating head. As represented in figure 14, the maximum temperature reached from the C/SiC and steel component are below the working limits in continuous service of the materials.

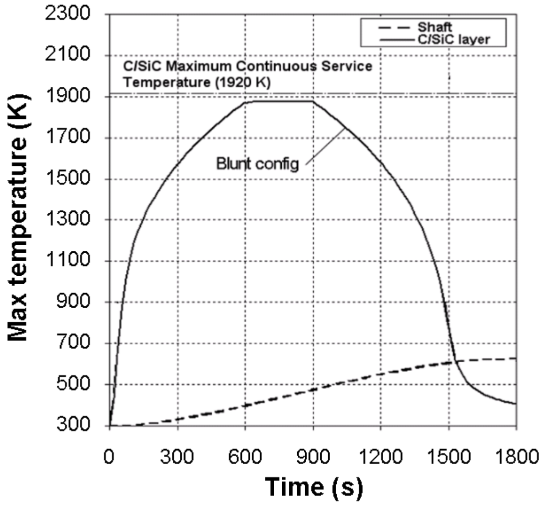

Figure 14. Max temperature points timeline in slat mechanism.

The structural analysis has the objective both to verify the state of stress of the C/SiC part and the displacements produced by the application of the dynamic pressure (figure 15).

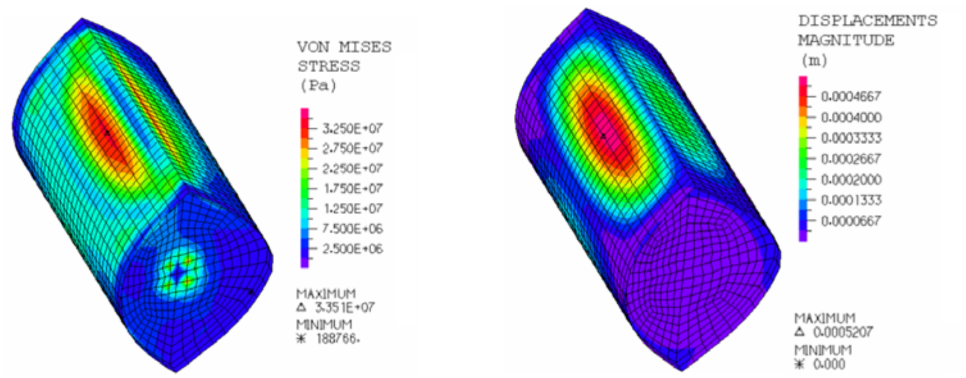

Figure 15. Von Mises stress and displacement magnitude bandplots for the slat mechanism.

The control on the displacements is important to verify that the head is not affected of a bending so high to produce an excessive gap with the rest of the wing surface. The model is built as a pipe, 1m of span, closed at the ends by two caps of same material; it is hinged-constrained at the ends where is located the clamping to the metal shaft.

The stress, calculated following the Von Mises criterion, do not get over 33.5 MPa (very low respect the material limit of 500 Mpa). The displacements reach a maximum value of 0.5mm. In figure 16 the temperature field in a heating/cooling sequence is reported for a 2D model.

For the compliant mechanism a complete finite element model needed to be realized because the bigger complexity of the concept not allowed to make a preliminary prediction of his behaviour. The results derived from the application of the heat flux and the boundary radiation show a maximum temperature (reached at time 900 sec – end of heating) of 1878 K (figure 16). With a radiative insulation, the averaged temperature of the ribs does not get over 600 K. This matter is important for the clamping to the rest of the wing box. This results is reached by introduction of some "holes" into the ribs structure. The holes create a shrinkage of the rib section and the increasing of the conductive thermal resistance. The heating/cooling sequence for this mechanism is reported in figure 19.

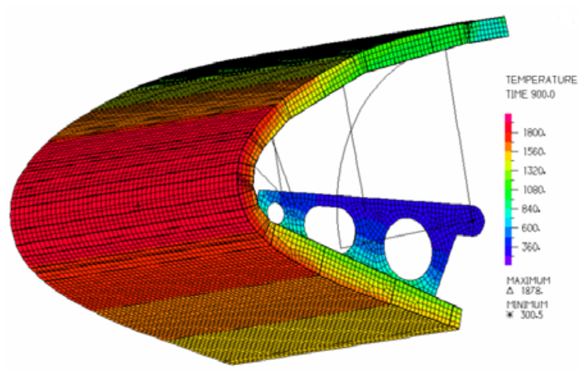

Figure 16. Temperature bandplot at time 900 sec for the compliant mechanism.

The results derived from the application of the dynamic pressure coupled to the thermal expansion effects show for an average stress state of 50 Mpa (figure 17). The ribs are more stressed with some peaks to 150 Mpa but still within C/SiC the material capability. Only locally (at the arms load introduction points) coming closer to the design allowable.

The maximum displacement is on the order of 3mm localized on the stagnation line and on the windward side.

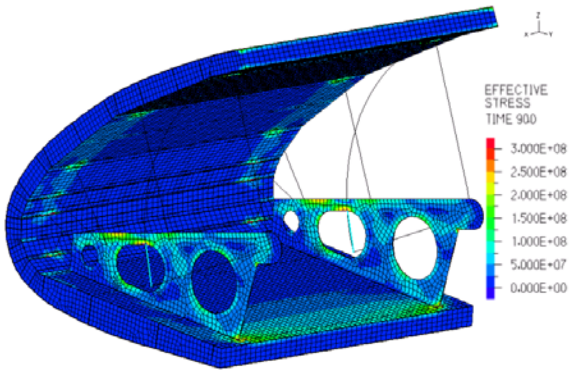

Figure 17. Von Mises stress bandplot at time 900 sec for the compliant mechanism.

8. CONCLUSIONS

This paper illustrates the design path followed and applied to the concept of a adapting structure with variable geometry. This concept is proposed on the morphing of a leading edge for a space transportation system with the aim to result advantageous in terms of performances and feasible in terms of production.

We remark that all the evaluations illustrated in this work belong to a concept phase. More analysis, i.e. for the aerodynamics and aerothermodynamics, in order to investigate more in detail the real feasibility and to optimize the benefits can be proposed as a next step.

ACKNOWLEDGEMENTS

The smart TPS activity was performed under ESA contract no 17770/03/NL/HE. The variable curvature thermal protection system is one of the branch in which this project is subdivided. Most relevant Smart TPS materials and concepts are identified and elaborated in this exploratory activity from the members of the team [14].

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APPENDIX

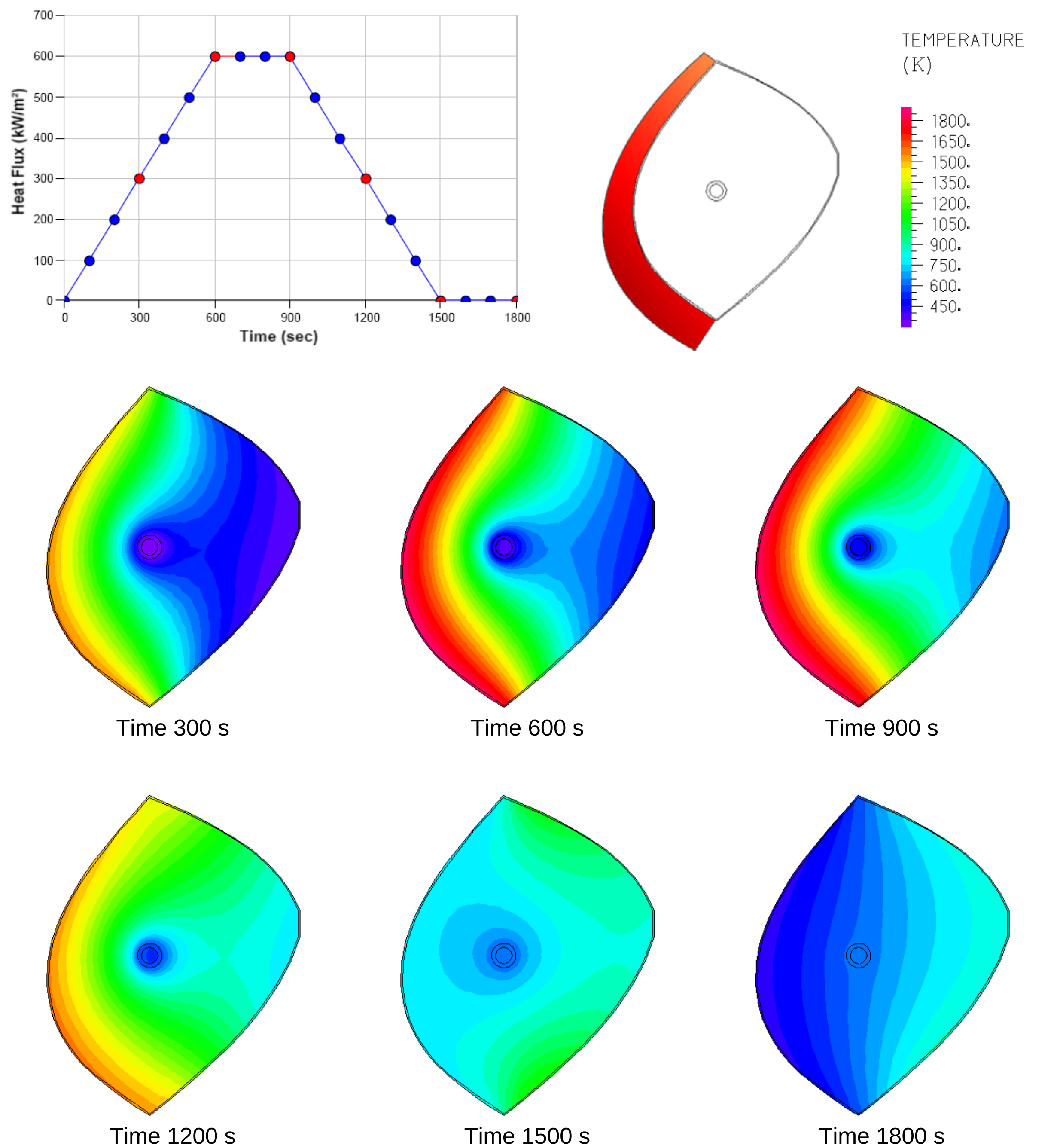

Figure 18. Heating/cooling sequence of the rotating head of the slat mechanism in blunt configuration.

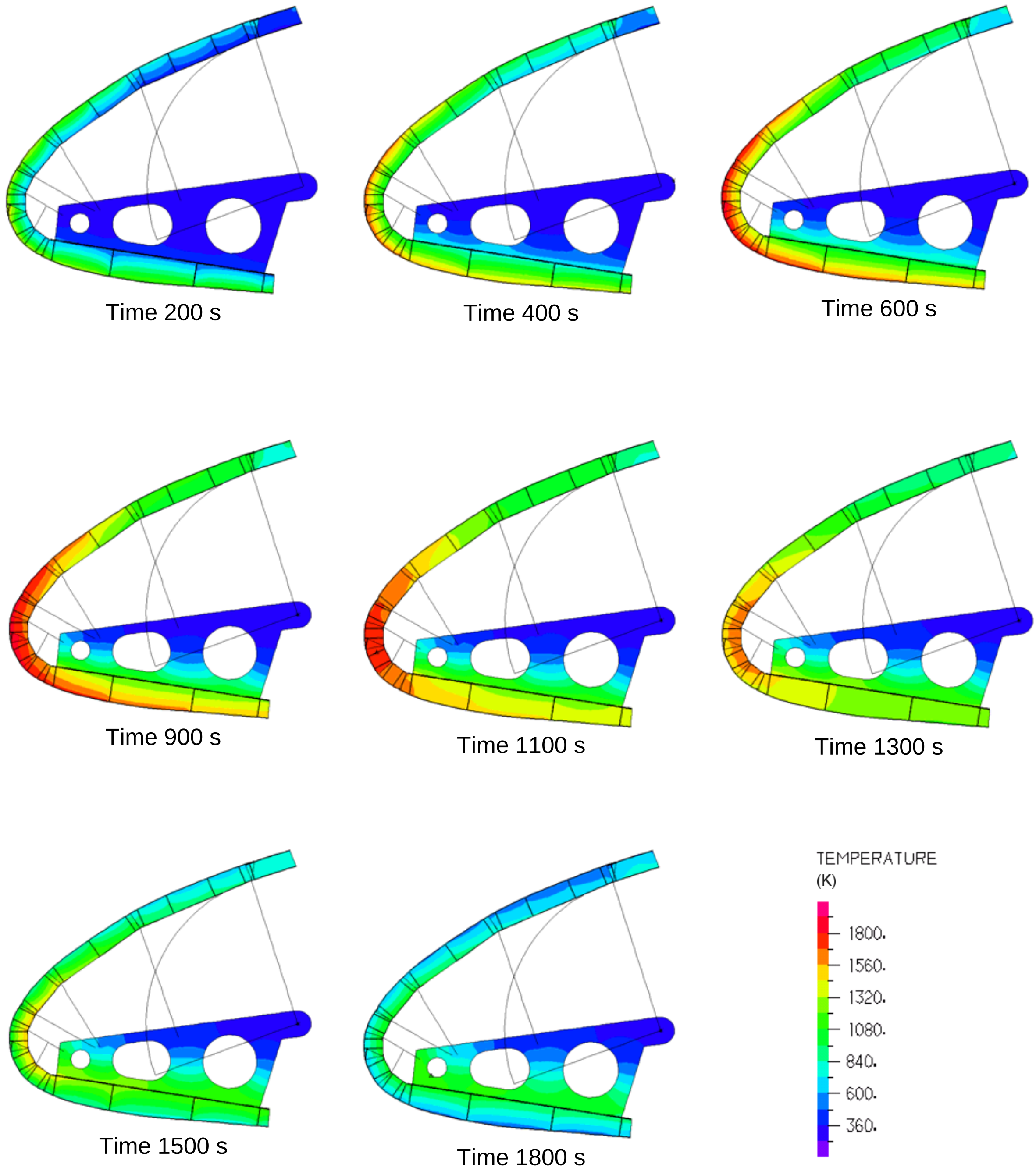

Figure 19. Heating/cooling sequence for the compliant mechanism in blunt configuration.

SESSION 4B

VIBRATION CONTROL I

CHAIRS:

A. Flatau, *University of Maryland*,

S. O. Moheimani, *University of Newcastle*