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Thermo-structural behaviour of an UHTC made nose cap of a reentry vehicle

Rosario Borrelli[a,*], Aniello Riccio[a], Domenico Tescione[a], Roberto Gardi[b], Giuliano Marino[b]

[a] *Computational Mechanics Lab., CIRA scpa, Italian Aerospace Research Centre, Via Maiorise, 81043 Capua (CE), Italy*
[b] *Space Programs Office, CIRA scpa, Italian Aerospace Research Centre, Via Maiorise, 81043 Capua (CE), Italy*

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Abstract

In the frame of the technology project sharp hot structures (SHS), focused on the assessment of the applicability of ultra-high temperature ceramics (UHTCs) to the fabrication of high performance and SHS for reusable launch vehicles, the nose cap demonstrator named Nose_2 has been tested in the plasma wind tunnel (PWT) facility. In this paper, the FEM based thermo-structural analyses, carried out for the rebuilding of this PWT test are presented.

Comparisons with experimental data measured in the PWT have been introduced to validate the FEM model and to help in interpreting the experimental test itself. Synergies between numerical and experimental activities have been finalized to the improvement of knowledge on the physical phenomenon under investigation.

The effects on the thermal response due to the assumption of the catalytic condition of the wall, due to the uncertainties related to heat flux and pressure measurements on the probe (which influence the heat flux computation) and due to uncertainties in the determination of some UHTC thermal properties, have been investigated.

The experimental temperatures curves falls very close to the numerical envelope (taking in account several sources of error) for all the test duration and the NCW model was found more reliable in reproducing thermal behaviour of the nose cap.

Keywords: Nose cap; Thermo-structural analyses; Rebuilding; UHTC; Hot structures

1. Introduction

The design of structures for winged vehicles that fly through the earth's atmosphere, either to and from space or in sustained flight, poses severe challenges to structural designers. The main problem for them is the aerodynamic heating which is the principal structural load because the induced high temperatures can affect the structural behaviour in several detrimental ways. First of all, high temperatures reduce noticeably elastic properties such as Young's modulus, moreover, allowable stresses are reduced and time-dependent material behaviour such as creep come into play. In addition thermal stresses are introduced because of impeded thermal expansions or contractions. Such stresses increase deformation, change buckling loads and alter flutter behaviour [1].

* Corresponding author. Tel.: +39 0823 623544.
E-mail addresses: r.borrelli@cira.it (R. Borrelli), a.riccio@cira.it (A. Riccio), d.tescione@cira.it (D. Tescione), r.gardi@cira.it (R. Gardi), g.marino@cira.it (G. Marino).

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Thus, in order to protect the vehicle's structure from the aerothermodynamic environment encountered during ascent and entry, thermal protection systems (TPSs) have to be adopted.

From the early 1950s up to nowadays three kinds of systems has been developed:

(1) Absorptive systems: absorption of the incoming heat by the surface material through heat sink, ablation transpiration cooling or convective cooling.
(2) Radiative systems: rejection of part of the incoming heat by thermal radiation from a suitable high temperature surface.
(3) Combined absorptive/radiative systems.

As an example, the current space shuttle orbiter TPS configuration has been designed to keep structural temperatures less than 450 K. The thermal protection is composed of two types of reusable surface insulation (RSI) tiles. The RSI tiles covering the orbiter are made of coated silica fibre. The two types differ only in surface coating to provide protection for different temperature environments. The low-temperature insulation (LRSI) consists of 8-in.-square silica tiles and covers the top of the vehicle where temperatures are less than 920 K. The high-temperature insulation (HRSI) consists of 6-in.-square tiles that cover the bottom and some leading edges of the orbiter where temperatures are below 1530 K.

In addition, reinforced carbon–carbon (RCC) is used for the nose cap and wing leading edges where temperatures are above 1530 K. Finally flexible reusable surface insulation (FRSI) and advanced flexible reusable surface insulation (AFRSI) are used at locations where temperatures are less than 640 K [1,2].

Much effort is currently dedicated in the aerospace community to study future vehicles reentering the earth atmosphere [3–5]. The word space agency and industries are trying to develop fully reusable space transportation systems able to perform multiple launches in a safe, cost-effective manner [6]. In order to match these requirements, future concepts for space launchers are addressed towards sharp hot structures (SHS).

This kind of architecture (aircrafts-like) offers several advantages with respect to current blunt shapes: manoeuvrability improvement, decrease of electromagnetic interferences and communication black-out and drag reduction during the ascent phase. As main negative aspect, the aerodynamic heat fluxes increase dramatically over the vehicle profile, exceeding conventional values of 650–800 kW/m^2. The conventional ceramic matrix composites (CMCs) such as C/C and C/SiC, although reliable and well tested, are not able to sustain so high thermal loads.

For these reasons, at the present time, lots of technology projects are moving towards ceramic protection systems based on hafnium, zirconium and titanium borides. These materials, known as ultra-high temperature ceramics (UHTCs), are characterized by very high melting point and, if blended with a proper reinforcing phase (such as silicon carbide, SiC), they exhibit good oxidation resistance. As matter of fact, in oxidation environment, up to 1500 °C and at atmospheric pressure, SiC undergoes passive oxidation with the formation of silicon dioxide (SiO_2). In regime of SiC passive oxidation the presence of zirconium and hafnium diborides leads to the formation of a vitreous borosilicate layer which, being characterized by a very low oxygen permeability, restricts the degradation processes to the surface of the ceramic sample [7–9].

Among these modern projects, the SHS program is focused on the assessment of UHTCs to the fabrication of high performance and slender-shaped hot structures for critical parts of reusable launch vehicles. These critical parts of re-entry vehicles, such as nose cap, has to be firstly qualified on-ground and then tested and validated in flight conditions. To this aim a dedicated plasma wind tunnel (PWT) test campaign has been designed on several technological demonstrator dubbed Nose_1, Nose_2 and Nose_x. They are full scale specimens, thus, the technological problems occurred during their manufacturing are the same that probably will recur when the launchers will be tested in flight condition.

In the present paper, the results coming from the thermo-structural rebuilding FEM analyses of the PWT test on Nose_2 are reported. The main aim is to demonstrate the capability of the adopted FEM tool to reproduce the real thermo-structural behaviour of the nose cap by comparing numerical temperature distribution to the experimental data obtained during the test. The numerical results are also used to give a reasonable interpretation of the experimental data and to help in understanding the thermo-mechanical behaviour of the nose cap subcomponents and their interactions during the test.

The paper is organized as follows:

The architecture of the Nose_2 and some considerations about its design are reported in Section 2. Afterward, in Section 3, the developed finite element model, reproducing the thermal–mechanical behaviour under the aero-thermal loads encountered in the PWT facility, is described in detail.

In Section 4 both the experimental data and a preliminary study aimed at supporting the interpretation of