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Research Paper

Structural and thermal analysis of integrated thermal protection systems with C/SiC composite cellular core sandwich panels

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HIGHLIGHTS

- The devised ITPS integrates light weight and high service temperature up to 1600 °C.
- The critical relative density of the failure models in the ITPS is identified.
- The effective thermal conductivity of the ITPS is derived and numerical verified.
- Preliminary sizing analysis identifies the acceptable dimensions of the ITPS.
- The ITPS incorporates much low areal density ρ_a and high effective specific heat C_{eff}.

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ABSTRACT

Current studies of the integrated thermal protection system (ITPS) are mainly focused on the metal corrugated core sandwich panels, resulting in low service temperature and high weight level. Here, by contrast, ITPS based on lightweight C/SiC composite sandwich panels with corrugated, pyramid as well modified pyramid cores are proposed for purpose of raising the service temperature, and lowering the weight level. As the basis, the structural analysis identifies the critical relative density of the failure models in the proposed ITPS, giving a guide to avoid the buckling failure. The effective thermal conductivity, which characterized the ability of heat conduction, is theoretically derived and numerical verified. Moreover, under typical aerodynamic heat and pressure, preliminary sizing analysis figures out the accepted dimensions of the ITPS with the fulfillment of both thermal and mechanical constraints. A new evaluate index: effective specific heat C_{eff} is proposed to compare the ITPS quantitatively and objectively. The comparison firmly confirms that the areal densities of the ITPSs with the proposed C/SiC pyramid and modified pyramid sandwich panels are much lower than those of the reported ITPSs with metal corrugated core sandwich panels. Meanwhile, the effective specific heat of the proposed ITPS is much higher than that of the reported ITPSs, revealing that the proposed ITPS incorporates the advantages of lower areal density and higher service temperature up to 1600 °C compared with the reported metal corrugated core ITPS.

1. Introduction

Thermal protection systems (TPS), such as ablative TPS [1], metallic TPS (MTPS) [2] and ceramic matrix composite (CMC) TPS [3], are widely known as one of the most key technologies to protect hypersonic vehicles from overheating [4]. To further reduce the weight, recently, efforts have been focused on developing integrated thermal protection system (ITPS) [5]. As illustrated in Fig. 1, a typical ITPS efficiently incorporates a cellular core sandwich panel played as load bearing structure, and filling materials acted as thermal insulation. Thus, the ITPS is a structurally and functionally integrated design concept, since it can simultaneously actualize the double functions of thermal protection and load bearing [6]. The feature advantage of the ITPS strongly depends on the sandwich panel whose cellular characteristic raises the promising prospect of reducing the weight of the whole system effectively.

To date, various studies focus on the ITPS, most of which are consist of metal corrugated core sandwich panels and insulation materials, resulting in not only low service temperature but also high weight level. For instance, titanium alloy corrugated sandwich was used in ITPS, with low temperature of 700 °C and high density

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Nomenclature

$\bar{\rho}$	relative density (%)
ρ	density (kg/m^3)
L	length of the face sheet (mm)
W	width of the face sheet (mm)
h	height between the face sheets (mm)
t	thickness of the face sheet (mm)
θ	angle between the bar/web and face sheet (°)
d	diameter of the bars in pyramid core (mm)
b	half size of the hat in corrugated core (mm)
t_s	thickness of the web in corrugated and modified pyramid core (mm)
a	half size of side length of additional web (mm)
u	length of the square cross section of the inclined bars in modified pyramid (mm)
α	half angle between the bars in modified pyramid (°)
E	Young's modulus (MPa)
σ	compressive strength (MPa)
R	thermal resistance (°C/W)
Rs	thermal resistance of C/SiC in the core (°C/W)
Rf	thermal resistance of the insulation material (°C/W)
λ	thermal conductivity (W/m °C)
A	cross section area (m^2)
T	temperature (°C)
V	volume (m^3)
C	specific heat (J/kg °C)
Q	the incident heat per area (J/m^2)

Superscripts

c	cellular core
s	bulk constituent
zz	mechanical variable act along the z axis
f	fracture
b	buckling
eff	effective
a	ambient

Subscripts

p	pyramid core
c	corrugated core
m	modified pyramid core
s	C/SiC
f	filling thermal insulation material
b	bottom face sheet
lim	allowable value
a	per area
max	maximum
total	total
pressure	physical quantity caused by pressure
thermal	physical quantity caused by thermal

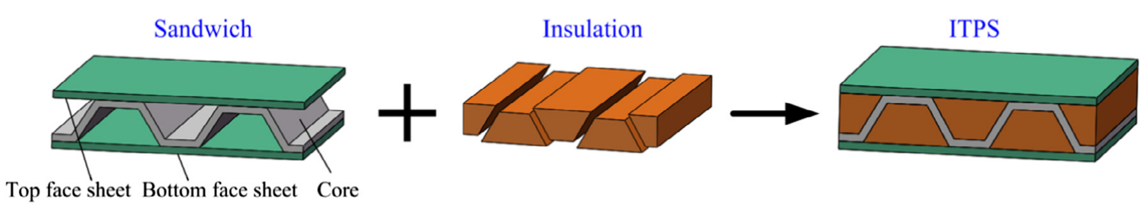

Fig. 1. A typical integrated thermal protection system (ITPS) includes the load bearing sandwich panel and the inner thermal insulation.

about 500 kg/m^3 [7]. Chromium alloy PM2000 corrugated sandwich was also used in the ITPS whose service temperature is of 1200 °C, and the density is about 730 kg/m^3 [8]. The inconel corrugated sandwich [9] and hybrid corrugated [10] or truss core [11] sandwich with inconel top face sheet (TFS) and aluminum alloy bottom face sheet (BFS) were studied. The service temperature is about 1200 °C, and the density is around 300–600 kg/m^3. Corrugated sandwich which is the combination of Aluminosilicate/Nextel720 TFS and beryllium BFS was also designed [12]. The service temperature is about 900 °C, and its density is about 130 kg/m^3. Besides, resin matrix composites, such as Graphite/Epoxy (T300/934) was also used in the fabrication of corrugated sandwich panels [13]. However, neither the metal alloys nor the resin matrix composites can fulfill the urgent need of high service temperature (usually up to 1500 °C), caused by the increasing high Mach number of the hypersonic vehicles. Moreover, compared with other cellular cores, such as lattice cores, currently used corrugated core is still not lightweight enough, leading to the disadvantage of overweight for the reported ITPS. The corrugated core also easily introduces significant heat short effect, always resulting in overheating of the BFS. Therefore, to further raise the service temperature, and to reduce the weight of the ITPS, it is necessary to explore new constituent and to carefully select cellular core for the sandwich panels.

To fundamentally understand the current state of art for the reported cellular core sandwich panels, an Ashby style plot of the service temperature versus density for typical sandwich panels is illustrated in Fig. 2. For instance, the wood based lattice truss has low density, while its service temperature is far below the required service temperature of ITPS [14]. Furthermore, it is obviously that most of the sandwich panels were fabricated from metals, such as stainless steel [15], aluminum alloy [16], nickel alloy [17], titanium alloy [18] and copper [19] which possess limited service temperature ranged from 300–1200 °C. Corrugated sandwiches made of ZrO_2 [20] and ZrB_2 [21] ceramics have high service temperature up to 1000–1600 °C. Whereas, their densities are much higher than those of the metal sandwiches. Carbon fiber reinforced polymers corrugated, NOMEX honeycomb and lattice core sandwiches [22–24] are also widely available. They have low densities, while their service temperatures are usually below 400 °C. Fig. 2 also reveals that the sandwich panels with lattice core, such as pyramid and truss, have much lower densities than those of the corrugated core sandwiches when they are made of the same constituents.

Actually, Fig. 2 reveals that the reported sandwich panels still cannot integrate both high service temperature and low density. Thus, in our recent works [25,26], cellular core sandwich panels with the new constituent of ceramic matrix composite (CMC) C/SiC have been proposed and fabricated. The inherent excellent