Composite Structures 188 (2018) 278–286

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Design of the corrugated-core sandwich panel with external active cooling system

S.A. Lurie[a,b,*], Yu.O. Solyaev[a,b], A.A. Koshurina[b], V.F. Formalev[c], V.N. Dobryanskiy[c], M.L. Kachanov[d,b]

[a] *Institute of Applied Mechanics of Russian Academy of Science, Moscow, Russia*
[b] *Nizhny Novgorod State Technical University Named After R.E. Alekseev, Nyzhny Novgorod, Russia*
[c] *Moscow Aviation Institute, Moscow, Russia*
[d] *Department of Mechanical Engineering, Tufts University, Medford, MA 02155, USA*

ARTICLE INFO

Keywords:
Sandwich panel
Corrugated core
External active cooling
Optimal structure

ABSTRACT

Optimal structure of thermal barrier skins used for rescue vehicles experiencing extreme conditions is developed. The conditions include extreme arctic cold and possible extreme heat of burning oil. The skin structure includes fibrous insulation material as well as external active cooling system using sprinklers. Optimal design variables, for the best combinations of the thermal and mechanical performances – the panel geometry and the discharge density – are examined by the analytic and numerical means. It is shown that the high discharge density in the cooling system may be necessary not only for the thermal protection, but also to provide the strength of the panel elements. In particular under the considered loading conditions, the solution of the optimization problem with all constraints exists only for the enough high discharge density due to the thermal buckling of the web elements inside the panel under non-uniform heating.

1. Introduction

We examine the optimal structure of thermal barrier skins used for the rescue vehicles experiencing extreme conditions. The conditions include extreme arctic cold and possible extreme heat (up to 1200 °C) of burning oil [1]. The skin structure includes fibrous insulation material as well as active cooling system using sprinklers. The optimal design, for the best combinations of the thermal and mechanical performances, involves the optimal choice of the panel geometry and of the discharge density.

Fiberglass is usually the structural material of choice for the similar vehicles or the freefall lifeboats; it possesses sufficient specific strength and stiffness. However, for the thermal protection against external cold and heat conditions the additional insulation is needed. As discussed in [1,2], the use of only the passive thermal protection leads to substantial increase of panel thickness and weight that may be unacceptable. Hence the passive protection should be supplemented by an active external cooling (sprinkler system). The coolant in this system may be a seawater; however, in its absence, one may be compelled to use the onboard supply. This is the reason we consider not only the mass minimization problem, but, also, the minimization of the discharge density in the cooling system.

We consider a panel with a corrugated core. General principles of optimal design of such panels have been developed earlier (see, for example, [3–7]). Note that sandwich panels with honeycomb core have higher mass efficiency, but their thermal protection characteristics are somewhat lower than those of corrugated core sandwiches, due to higher values of the effective thermal conductivity in the transverse direction [8,9]. As far as foam core is concerned, it has good thermal insulation properties but poor mechanical characteristics [8–10].

Sandwich panels with corrugated cores are often the best option for multifunctional structures: they have sufficient load bearing capacity and thermal protection [9]. The design of such panels has been discussed in a number of works; for the passive thermal protection, see the works [11–14]. It has been shown, in particular, that the conditions of thermal protection and thermal buckling of the core elements constitute the most serious constraint. It has also been found that analytical one-dimensional solutions allow one to obtain sufficiently accurate estimates of the thermal state of the panels under transient heating conditions across thickness. The panels with an internal active convective cooling system that use water were analyzed, in the context of structural an hydrodynamic parameters, in [14–17].

The present work aims at the optimization of geometry of a load-bearing and thermal protection panel with an active external cooling

---

[*] Corresponding author at: Leningraskiy ave., 7, Moscow, Russia.
E-mail address: salurie@mail.ru (S.A. Lurie).

https://doi.org/10.1016/j.compstruct.2017.12.082
Received 29 September 2017; Accepted 28 December 2017

system. The interior of the panel contains an insulating fibrous material, to provide the passive thermal protection. We note that the active cooling system may be of three distinctly different types: transpiration, film cooling, and convective cooling [18]. The sprinkler system produces a "film" cooling (a thin layer of water flow on the vehicle surface). We proposed a simplified evaluation of the thermal state of the panel with such cooling system.

We solve the optimization problem using the methodology of optimization under constraints. Finite element simulations are carried out, and compared to the analytical solution. Optimal variants of panel structure are identified.

2. Modeling of the structure of the panel

We suggest simple analytical models for the effective thermal properties of the panel, for the cooling process, for the structural strength of the panel under mechanical loading and for thermal buckling of its elements caused by non-uniform temperature distribution.

2.1. Structure of the panel and its effective thermal properties

We consider a sandwich panel with corrugated core (a "web") shown in Fig. 1 where notations are as follows. The face thickness is t_f, the web thickness is t_c and the core depth is h_c, The distance between the web elements is d_f, the corrugation pitch is $2p$, and the angle between the web and the vertical direction is θ. The total panel thickness is $h = h_c + 2t_f$. Total area of the load bearing elements in the panel cross section is $A = 4t_f p + 2t_c(d_f + h_c/\cos\theta)$. The panel length $a = 1200$ mm and its width $b = 500$ mm. Heat-insulating fibrous material fills the free space inside the panel. In the following, we use parameter $N = a/(2p)$ for the number of core pitches. Internal panel surface is located at $z = 0$ and the external one at $z = h$ in the coordinate system shown in Fig. 1(b). The panel is placed on the lateral vertical wall of the vehicle that has mass M, length L, width is W, and height H.

Thus, the average mass density of the panel is

$$\rho = \frac{2\rho_f V_f + \rho_c V_c + \rho_i V_i}{V} \tag{1}$$

The effective heat capacity and thermal conductivity, evaluated by the law of mixtures (that was shown in works [1,11,12] to be sufficiently accurate for the structures of this kind) are given by

$$c = \frac{2\rho_f c_f V_f + \rho_c c_c V_c + \rho_i c_i V_i}{\rho V} \tag{2}$$

$$k = \frac{2k_f V_f + k_c V_c + k_i V_i}{V} \tag{3}$$

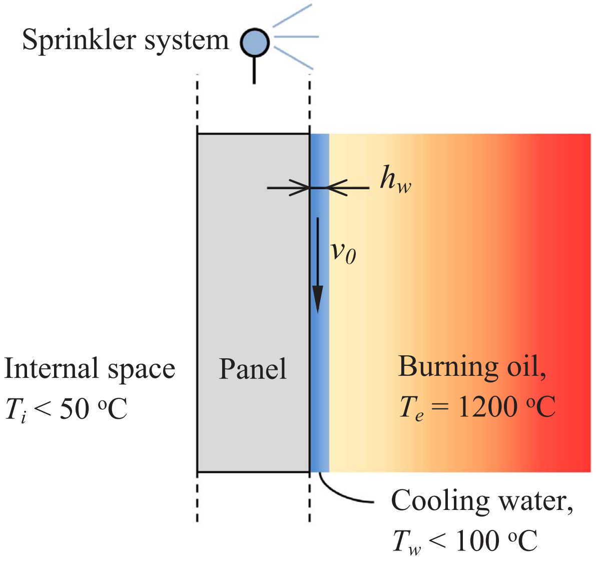

Fig. 2. Model of the external active cooling system.

where $V = 2p\,h$, $V_f = 2p\,t_f$, $V_c = 2t_c(d_f + h_c/\cos\theta)$, $V_i = V - 2V_f - V_c$.

2.2. Analysis of the external cooling process

For thermal protection of the vehicle, as it passes through burning oil, an external sprinkler system is used (Fig. 2). This system supplies water (or other cooling liquid) through the sprinkler heads mounted at the top of the vehicle; its temperature will be assumed $T_0 = 20\,^\circ$C. Water flows down along the outer surface of the vehicle under the action of gravity, thus protecting the vehicle. The discharge density η (that specifies how much water is spread, per minute, over a part of the cooled surface area of one square meter) is usually below $20\,\mathrm{L{\cdot}min^{-1}{\cdot}m^{-2}}$ (or $3.33\ 10^{-4}$ m/s in the Si-system).

For the analysis of the cooling process, the following assumptions will be used:

1) The flow of water is laminar, of constant thickness h_w (Fig. 2);
2) The flow is uniformly heated through the thickness to temperature $T_w(t,y)$;
3) No boiling occurs;
4) The heat dissipation due to evaporation is neglected.

The thickness of the water flow h_w is controlled by the discharge density η and flow velocity v_w. Water moves, driven by gravity, along

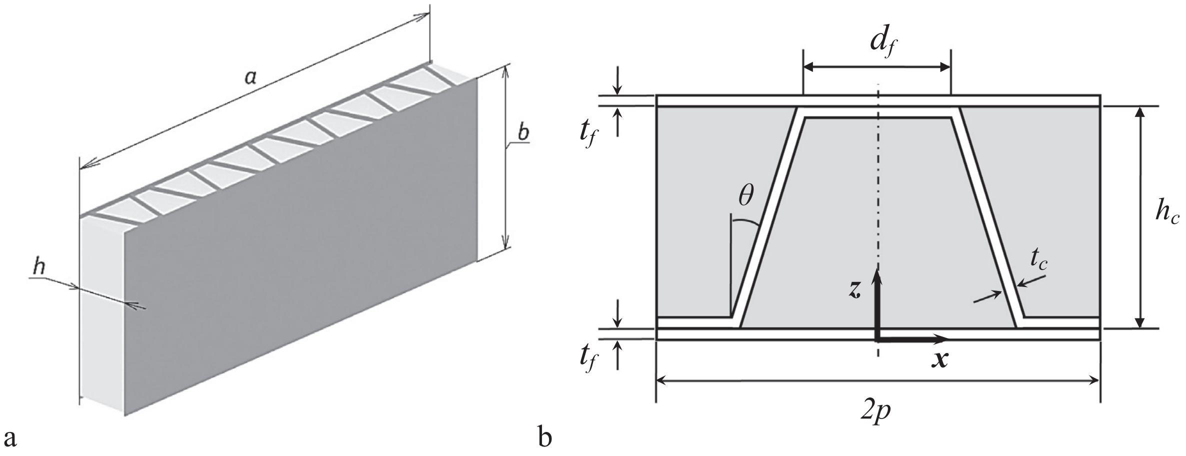

Fig. 1. Corrugated core sandwich panel (a) and its unit cell (b).