Thermomechanical performance of bio-inspired corrugated-core sandwich structure for thermal protection system panel

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1. Introduction

Thermal protection system (TPS) of a hypersonic vehicle is required to be lightweight while providing high strength under dynamic and acoustic pressures and withstanding aerodynamic heating during hypersonic flight. During their service lifetime, the hypersonic vehicle will serve in a harsh condition such as high aerodynamic heating on the surface which results in a thermal gradient across the thickness direction of the TPS panel [1, 2]. At the meantime, thermal stress will be increased, which cause the TPS panel to deflect outwardly and may damage the vehicle [3]. In addition, the outward deflection of the TPS panel may cause a transition from laminar to turbulent boundary conditions, which may increase local aerodynamic heating [4]. Thus, the key design of the TPS panel is to ensure the vehicle structural temperature below the allowance temperature of the internal structure's material [5]. Besides that, it must also provide an acceptable surface deflection to prevent flow transition during flight. Most of the research focused on the goal of the temperature limit in the internal structure of the vehicle, they determined the proper thickness and material for the TPS panel. Thus, the concerns about the limit deflection and permanent deformation of the TPS panel are also important. In our previous design of the TPS panel [3], We employed an Inconel superalloy for the outer plate of the TPS panel which directly exposed to the high aerodynamic heating. However, this plate made of Inconel superalloy is heavy even though it guarantees the high strength for the TPS panel. Therefore, in this study, we will propose lightweight structures that also ensure the high strength for the TPS panel.

One of the light-weight candidate structure is sandwich structures which have been widely used in hypersonic vehicles as a thermal protection structure. Recently, sandwich structures consisting of two solid face sheets and a low-density core are inspired from biological structures [6, 7]. Due to a long evolution of nature, the biological structures are optimized to survive and adapt in the various environmental conditions. Thus, it is such a lightweight and high-strength structure for modern engineering applications. Many researchers have designed and investigated thermal-mechanical performances of the sandwich structure under various conditions such as crushing test [6], aerodynamic heating [5]. In this study, a bio-inspired sandwich structure is also proposed as a candidate structure for the outer surface of the TPS panel. The corrugated core of the sandwich panel is inspired and modified from the microstructure of Mantis shrimp's hammer [8]. The sinusoidal shape is shown in Fig. 1. In the present paper, numerical simulation of unidirectionally and bidirectionally corrugated core sandwich panel are modeled and investigated under aerodynamic heating. A comparison between the two proposed structures is discussed in term of thermal stress and thermal deflection limits.

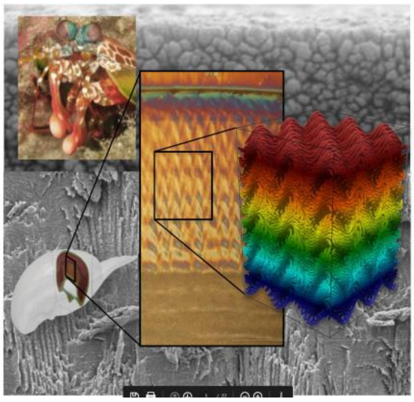

Fig.1. Sinusoidal structure of Mantis shrimp's hammer [8].

2. Bio-inspired corrugated core panel

Unit cells of the unidirectionally and bidirectionally corrugated core sandwich panel are shown in Fig. 2. The sandwich panel consists of 8×8-unit cells, which is 170 mm in length. For a purpose of future fabrication of the corrugated core sandwich structure, the top and the bottom of the corrugated core are fatted to fix to the upper and lower face sheets, respectively. Lightweight is our main goal in designing the outer surface for the TPS panel except for thermal stress and thermal deflection limits. The density of each part in the whole sandwich structure is required to be lower.

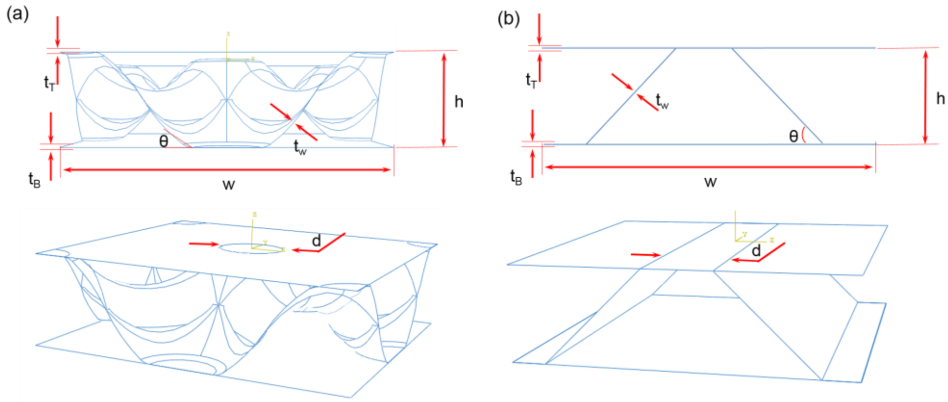

Fig.2. Conceptual design of a unit cell, unit: mm. (a) bidirectional core; (b) unidirectional core.

3. Numerical simulation

Due to large Young's modulus and fracture toughness, two metallic materials, Inconel 625 superalloy and stainless steel (SS304) are selected for the corrugated core sandwich structures. Two heating loads are applied on the top side of the corrugated core structures, as shown in Fig. 3. These heating rates are taken from simulation data at two locations in a hypersonic vehicle developed by NASA [4]. The simply supported boundary condition is applied at the edges of the side of the structures. The material temperature dependent is used to fully consider the material behavior at high temperature. A three-dimensional simulation is conducted in ABAQUS software.

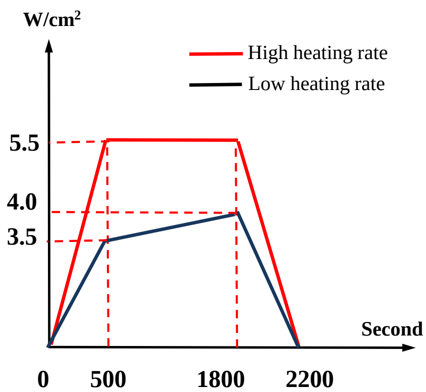

Fig. 3. Heating rates applied in the simulation [4].

4. Results and discussion

Fig. 4 shows the displacement contour results of unidirectionally and bidirectionally corrugated core sandwich structures. The maximum deflections at 530 sec are 1.27 mm and 1.42 mm for unidirectional and bidirectional core panels, respectively when the temperature difference between upper and lower face sheets reaches a maximum value. Fig. 5 shows the Mises stress contours at the time of simulation mission (5000 sec). The maximum Mises stresses are 364 MPa and 439 MPa for unidirectional core and bidirectional core panels, respectively. This accumulated stress was found at several areas in the core near the edges of the panel. The high stress could cause a permanent deformation at that local area. However, in the design of the TPS panel, we also use a thin foil of material to enclose the edges of the TPS panel, hence, we would state that the accumulated high stress is acceptable for the TPS panel.

In order to compare the effectiveness of proposed corrugated core structures to the solid structure used in our previous research [3], we also performed the thermo-mechanical model of the solid structure made of Inconel material. The maximum deflection was just 0.14 mm which was satisfied the limit deflection for the outer surface of the vehicle, as shown in Fig. 6; however, the weight of the solid structure was 0.62 Kg while that of the corrugated structure was 0.21 Kg. Blosser et al. [1] proposed a criterion for deflection limit of the outer surface which should be less than 1% of the main diagonal span of the TPS panel. Thus, the proposed corrugated core panels satisfied the limit deflection, moreover, their weights are more compatible than that of the previous design of the solid panel. Therefore, in term of weight and deflection limit, we could conclude that the proposed corrugated core structure is an excellent candidate structure for the outer plate of the TPS panel.

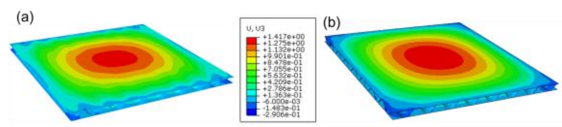

Fig. 4. Simulation results for unidirectionally and bidirectionally corrugated core sandwich structures. Displacement contour at 530 sec (a) Unidirectional core; (b) Bidirectional core.

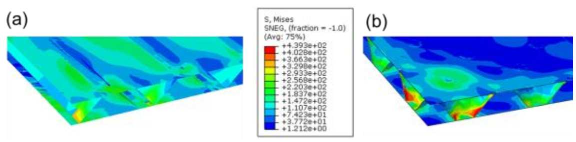

Fig. 5. Simulation results for unidirectionally and bidirectionally corrugated core sandwich structures. Mises stress contour at 5000 sec (a) Unidirectional core; (b) Bidirectional core.

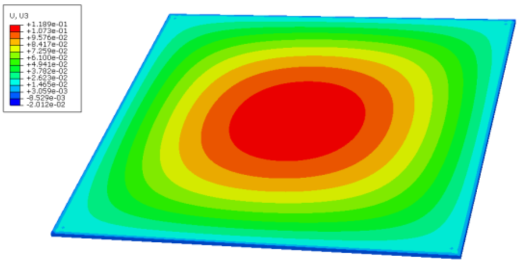

Fig. 6. Simulation results of a solid Inconel panel: displacement contour at 530 sec.

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