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Special Issue Paper

Thermal Characteristics of Hybrid Insert for Carbon Composite Satellite Structures

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ABSTRACT: Composite sandwich structures are widely employed in various applications, due to their high specific stiffness and specific bending strength compared to solid panels. Lately, for that reason, the advanced composite sandwich structures are employed in satellite structures: materials should be as light as possible with the highest attainable performance. This study is majorly focused on inserts employed to the composite sandwich satellite structures. A new hybrid insert design was developed in precedent study to reduce the mass of the sandwich structure since the mass of the satellite structure is related to high launching cost [1]. In this study, the thermal characteristics and behavior of the precedently developed hybrid insert with carbon composite reinforcing web and the conventional partial insert were numerically investigated.

Key Words: Composite, Insert, Satellite, Payload, Thermal property

1. INTRODUCTION

For space applications, materials should be as light as possible with the highest attainable performance. Although, absolute values of stiffness and strength are two criteria for selecting a material in fact, the ratio of stiffness to mass and strength to mass, the so called specific stiffness and specific strength, are usually used to satellite structures because launching cost of satellites is about $20,000-$50,000/kg [2]. Additionally, high specific stiffness is needed to increase the natural frequencies of a satellite and its components that is, resonance vibrations due to low frequency excitations of the launch vehicle must be avoided. Therefore, honeycomb sandwich structures are widely employed in aerospace structures because they have very high specific strength and stiffness compared to solid panels. Sandwich panel face sheets are commonly fabricated using aluminum or carbon/epoxy composite panels which carry the axial loads, bending moments, and in-plane shears while the core carries the normal flexural shears [3-5].

In precedent study, a new hybrid insert was designed to reduce the mass of the carbon/epoxy composite aluminum honeycomb sandwich structures joined with inserts since the mass of the satellite structure is related to high launching cost [1]. In this study, since high thermal conductance is important in through-thickness direction in satellite structures due to the heat generated form payloads, the thermal characteristics and behavior of the precedently developed hybrid insert with carbon composite reinforcing web and the conventional partial insert were numerically investigated.

2. THERMAL CHARACTERISTICS OF THE INSERT STRUCTURE

The main function of small-satellite thermal subsystem is to control temperature ranges specified in equipments and payload. The structure made of different materials such as carbon/epoxy composite and aluminum can generate thermal stresses without external constraints even under uniform temperature because the most materials have non-zero coefficients of thermal expansion [6]. Electronic and mechanical equipments of spacecrafts usually operate only within relatively narrow temperature ranges. Therefore, thermal design of spacecraft is required to control the temperature of satellite structures, equipments, and payloads within the operating temperature range [2,7].

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Actual thermal design of the satellite structure is complicated, because a satellite thermal design typically combines multiple modes of heat transfer with time varying boundary conditions that require transient instead of steady-state solutions. The temperature of a satellite structure depends on the balance between the heat received from external and internal sources, and the heat radiated to space. In order to control spacecraft temperatures, it is necessary to control the heat absorbed, the heat radiated or both [8].

The earliest spacecraft, such as Vanguard 1, typically required a power raising capability of only ~1 W, whereas current communications satellites typically require three orders of magnitude greater than this [2]. Typically, the payloads of the satellites dissipate heat during operation time. In case of Science and Technology Satellite III (STSAT III), average heat dissipation from the payloads is 30 W whereas the payloads of the larger satellites such as meteorological or communications satellites dissipate heat in kilowatts level [9]. To maintain the payloads temperature within the operating temperature ranges, there are two ways to control the temperature; passive and active thermal control techniques. The passive thermal control techniques consist essentially of the selection of surface properties, the control of conduction paths and thermal capacities and the use of insulation systems. The active thermal control techniques use heat pipes or radiators [10].

The hybrid insert with carbon composite reinforcing web developed in precedent study, is the case of passive thermal control technique especially with the control of conduction paths. The conventional partial insert with foam adhesive resin have two main heat path steps through the partial insert and the potting material of low thermal conductivity. While, the hybrid insert with carbon composite reinforcing web only has one heat path through the aluminum insert which has high thermal conductivity as shown in Fig. 1. In this study the equivalent thermal conductivities of the conventional and the hybrid insert structures were numerically calculated and compared.

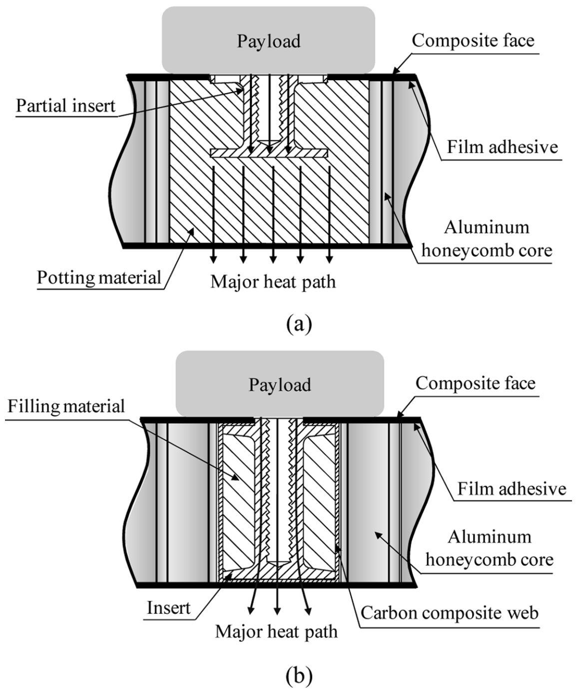


Fig. 1. Schematics of the heat path in the insert structure: (a) Conventional partial insert, (b) Hybrid insert

3. MATERIAL THERMAL CONDUCTIVITIES

Heat transfer through sandwich structures can be separated into the contributions of their faces, cores, and adhesive layers. Generally, the thermal resistance through the thickness of adhesive layer is negligible due to its thin thickness of the order of 0.1 mm. The heat transfer through a carbon/epoxy composite face and a honeycomb mainly occur by the conduction because the convection in the honeycomb cell is negligible due to its long and slender cell shape [11].

3.1 Carbon composite face

The high strength carbon/epoxy composite (USN 150, SK Chemicals, Republic of Korea) which is made of PAN (Polyacrylonitrile) based carbon fiber was used for the composite face material and the properties are shown in Table 1.

The composite face with stacking sequence of $[0/90]_S$ was fabricated in an autoclave vacuum bag degassing molding method using a cure cycle as shown in Fig. 2. The thickness of the cured high strength carbon/epoxy composite face was 0.5 mm and its elastic moduli, E_x and E_y, were 70.6 GPa which

Table 1. Properties of USN 150 (high-strength carbon epoxy)

	Longitudinal modulus E_1 [GPa]	Transverse modulus E_2 [GPa]	Poisson's ratio ν_{12}	Shear modulus G_{12} [GPa]
USN 150	130	10.5	0.28	4.4
USN 150 $[0/90]_S$	70.6	70.6	0.042	4.4

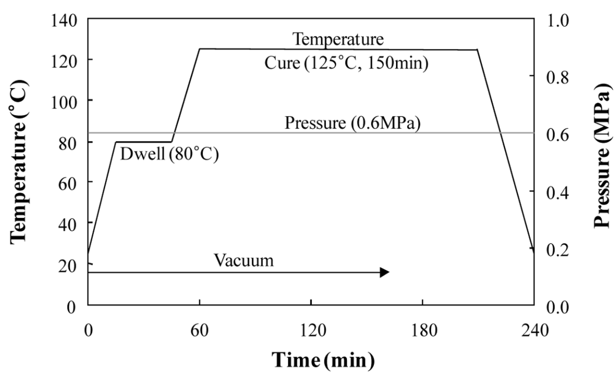
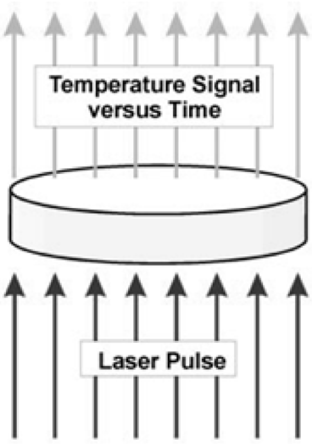
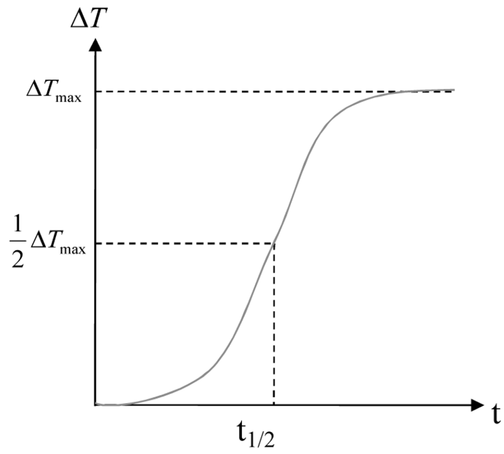


Fig. 2. Curing cycle for the carbon composite faces (USN 150)



(a)



(b)

Fig. 3. Flash method of measuring the thermal conductivity: (a) Principle, (b) Temperature rise at the rear surface of the sample

was calculated by the classical laminate theory [12].

The thermal conductivity of the composite face was measured by the flash method [13]. The cured carbon/epoxy composite face was cut as a disk shape with the diameter of 38 mm as shown in Fig. 3(a). The surface of the carbon/epoxy composite disk was coated with a thin layer of gold by sputtering the gold on the surface of the specimen, and then a graphite film was sprayed onto the gold layer. The xenon flash lamp irradiated a pulse at the sample's lower surface, while the infrared detector measured the temperature rise of the sample's top surface as shown in Fig. 3(b).

It is based on depositing a very short but intense energy pulse on one surface of a disk shaped sample, while monitoring the temperature change of the opposite face. From the characteristic time dependence of the temperature rise, called thermogram, the thermal diffusivity α (m^2/s) can be calculated using Parker's formula [13].

$$\alpha = \frac{1.38d^2}{t_{1/2}} \tag{1}$$

where, d is the sample's thickness and $t_{1/2}$ is the time necessary for the signal to reach 50% of its maximum value. After measuring the thermal diffusivity α of the sample, the thermal conductivity k (W/m·K) of the sample was calculated as follows [13].

$$k = \alpha \rho C_p \tag{2}$$

where, ρ is density (kg/m^3) and C_p is specific heat capacity (J/kg·K). The calculated thermal conductivities of the carbon/epoxy composite face were 21 W/m·K, 21 W/m·K and 0.68 W/m·K in the x, y and z directions, respectively.

3.2 Aluminum honeycomb core

The aluminum honeycomb made of 5052 aluminum alloy (Alcore Corp., USA) was used as the core material which has 6.35 mm cell size, 83 kg/m^3 density, 60 μm foil thickness and honeycomb thickness of 20 mm. The aluminum honeycomb core is a perforated type, where holes of 0.2 mm diameter on the wall are made for space applications such as high vacuum environment. The cell size of the honeycomb S is defined as the distance between two opposite walls in a honeycomb hexagon as shown in Fig. 4.

Where the x and y directions (lateral direction) of the aluminum honeycomb cells are defined in parallel and normal directions to the corrugation, respectively. The z direction is

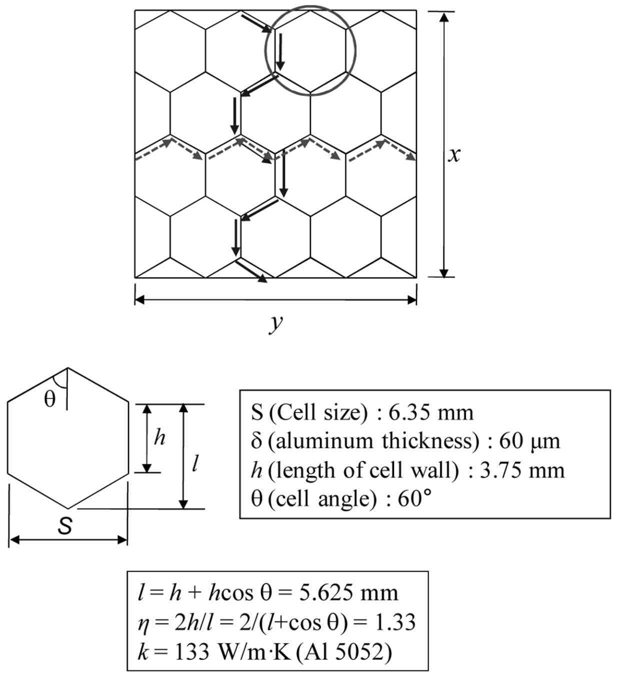


Fig. 4. Aluminum honeycomb panel used for the composite sandwich satellite structure

defined as the direction perpendicular to the *x-y* plane. The thermal conductivities, such as $k_{honeycomb\_x}$, $k_{honeycomb\_y}$ and $k_{honeycomb\_z}$, of the aluminum honeycomb panel are expressed with formulas as follows [14,15].

$$k_{honeycomb\_x} = \frac{2k_{al}\delta}{\eta S} \quad (3)$$

$$k_{honeycomb\_y} = \frac{k_{al}\delta}{S} \quad (4)$$

$$k_{honeycomb\_z} = \frac{2k_{al}\delta\eta}{S} \quad (5)$$

where,

$$l = h + h\cos\theta = 5.625 \text{ mm} \quad (6)$$

$$\eta = \frac{2h}{l} = \frac{2}{l+\cos\theta} = 1.33 \quad (7)$$

where, k_{al} is the thermal conductivity of 5052 aluminum alloy (133 W/m·K). The calculated thermal conductivities of the aluminum honeycomb panel were 1.97 W/m·K, 1.31 W/m·K and 3.50 W/m·K in the *x*, *y* and *z* directions, respectively.

4. EQUIVALENT THERMAL CONDUCTIVITIES OF THE INSERT STRUCTURES

To compare the thermal behavior of the conventional partial insert to that of the hybrid insert with carbon composite reinforcing web, the equivalent thermal conductivities of each insert structure was numerically calculated. In order to calculate the portion of area which one insert contributes to the equivalent thermal conductivity, the total contacting area of the payloads on the sandwich panel was divided by the total inserts employed. The calculated equivalent area per insert was 660 mm^2 with the diameter of 50 mm. To calculate the equivalent thermal conductivities of the composite sandwich panel with inserts, two different equivalent thermal circuits were built for each different insert structure case [16].

4.1 Conventional partial insert

The circuit for the conventional partial insert structure was composed of five different material elements. The conventional partial insert structure was potted with foam adhesive (FM 410-1, Cytec Industries Inc., USA). The thermal properties of each material for the conventional partial insert model are listed in Table 2.

The shape of the thermal circuit model of the composite sandwich panel with the conventional partial was disk with the diameter of 50 mm and the height of 21 mm. The carbon composite structure with the conventional partial insert was characterized by series-parallel configurations as shown in Fig. 5.

Table 2. Thermal conductivities of the insert materials

Conventional partial insert		Hybrid insert with carbon composite reinforcing web	
Material	k (W/m·K)	Material	k (W/m·K)
Insert *k1*	173	Insert *k1*	173
Composite face *k2*	0.68	Composite face *k2*	0.68
Film adhesive *k3*	0.05	Film adhesive *k3*	0.05
Foam adhesive *k4*	0.14	Foam adhesive *k4*	0.18
Honeycomb core *k5* (thickness)	3.5	Honeycomb core *k5* (thickness)	3.5
		Composite web *k6*	21

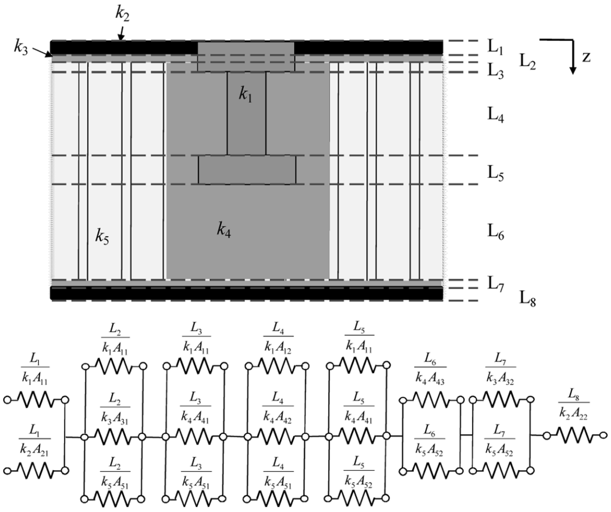


Fig. 5. Equivalent thermal circuits for a carbon composite structure with the conventional partial insert

Each section was divided in through-thickness direction of the sandwich structure with the insert. The heat flow was assumed to be one-dimensional, and the total thermal resistance R_{tot} was expressed as follows [16].

$$R_{tot} = \sum R_t \quad (8)$$

The calculated value of the total thermal resistance R_{tot} for the conventional partial insert sandwich structure was 2.64 K/W. The equivalent thermal conductivity k_{tot} of the conventional partial insert structure was calculated to be 4.04 W/m·K.

4.2 Hybrid insert with carbon composite reinforcing web

The circuit for the carbon composite reinforced insert structure was composed of six different material elements. The thermal properties of each material for the hybrid insert with carbon composite web model are listed in Table 2. The shape of the thermal circuit model of the composite sandwich panel with the carbon composite web reinforced insert was disk with

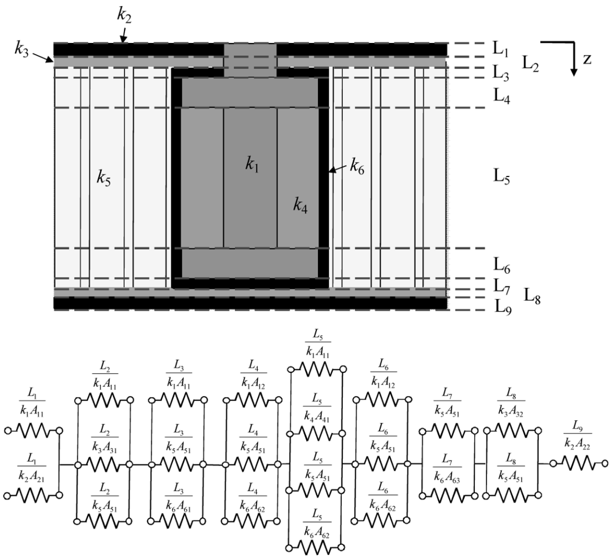


Fig. 6. Equivalent thermal circuits for a carbon composite structure with the carbon composite reinforced insert

the diameter of 50 mm and 21 mm height. It consists of the composite sandwich panel with the hybrid insert with carbon composite reinforcing web with foam epoxy filler (SMC 300, SK Chemical, Republic of Korea). Carbon composite structure with the carbon composite reinforced insert was characterized by series-parallel configurations as shown in Fig. 6.

Each section was divided in the through-thickness direction of the sandwich structure with the insert and the heat flow was assumed to be one-dimensional, and the total thermal resistance R_{tot} was expressed as Eq. (8). The calculated value of the total thermal resistance R_{tot} for the hybrid insert with carbon composite reinforcing web sandwich structure was 1.72 K/W. The equivalent thermal conductivity k_{tot} of the insert structure from calculated R_{tot} was 6.22 W/(m·K).

From the results, the hybrid insert structure with the carbon composite reinforcing web has 1.54 times larger equivalent thermal conductivity than that of the conventional partial insert structure. This means that the hybrid insert with carbon composite reinforcing web has better ability to conduct the heat generated from the payload than the conventional partial insert. This could give advantages in thermal design of satellite structures by eliminating or reducing the active thermal cooling systems.

5. CONCLUSION

The thermal characteristics and behavior of the precedently developed hybrid insert with carbon composite reinforcing web and the conventional partial insert were numerically investigated. The precedently developed hybrid insert with carbon composite reinforcing web, is the case of passive thermal control technique especially with the control of conduction paths. The conventional partial insert with foam adhesive resin have two main heat path steps and the potting material itself has low thermal conductivity, while the hybrid insert with carbon composite reinforcing web only has one heat path through the aluminum insert which has high thermal conductivity.

The thermal conductivity of the carbon/epoxy face was measured using the flash method. The calculated thermal conductivities of the carbon/epoxy composite face were 21 W/m·K, 21 W/m·K and 0.68 W/m·K in the *x*, *y* and *z* directions, respectively. Also, the calculated thermal conductivities of the aluminum honeycomb which was made of 5052 aluminum alloy was 1.97 W/m·K, 1.31 W/m·K and 3.50 W/m·K in the *x*, *y* and *z* directions, respectively.

The equivalent thermal conductivities of the conventional partial insert structure and the hybrid insert with the carbon composite web was numerically calculated and compared. The calculated results showed that the hybrid carbon composite reinforced insert increased the equivalent thermal conductivity of the sandwich structure by 54% compared to that of the conventional partial insert sandwich structure. Since the hybrid insert with the carbon composite reinforcing web has better ability to conduct the heat generated from the payloads than the conventional partial insert, the additional thermal cooling systems could be eliminated or reduced in the satellite structure. Consequently the total mass of the satellite could be reduced and also the total power needed to operate the cooling system could be also reduced.

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