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Composite Grid Structure with Near-Zero Thermally Induced Deflection

K. Joon Yoon,* Hoon C. Park,† H. J. Lee,‡ and C. K. Kim‡
Konkuk University, Seoul 143-701, Republic of Korea

A cost-saving manufacturing process is proposed to construct a carbon/epoxy square grid structure with near-zero coefficient of thermal expansion (CTE) in the three principal directions. Stacking sequences of the slotted joint rib and square tube are selected such that the individual member has near-zero CTE from an analysis using classical lamination theory. Pressure to bond ribs and tubes is provided by the thermal expansion of silicon rubber. Experimental results have shown that thermally induced deformation of a carbon grid panel is much less than that of an aluminum honeycomb sandwich panel. A numerical test has demonstrated that thermally induced deformation of the composite square grid structure is almost zero.

Introduction

SPACE structures are usually exposed to severe thermal environment. As an example, temperature at a sunny side of a solar panel can reach 100–120°C. On the other hand, temperature at the opposite side may stay at −150°C. This high temperature gradient can cause thermally induced distortion of the solar panel. Other space structures such as parabolic antennas can face a similar situation. This undesirable thermally induced deformation may eventually result in malfunction of the host spacecraft. Therefore, dimensional stability of each substructure under temperature variation is very important. The lightest structure with near zero coefficients of thermal expansion (CTE) and high stiffness/strength is the most suitable candidate for the aerospace applications. A composite grid structure with near-zero CTE in the three-dimensional directions can be one of the structures satisfying this requirement.

Even though the concept of a composite grid structure was established in the late 1970s, no satisfactory composite grid structure was developed as a result of the difficulty in manufacturing of the grid structure. In the early 1990s the Air Force Phillips Laboratory manufactured the first successful, high-quality composite isogrid structure. The isogrid structure is used for the solar array panel of the Clementine spacecraft.[1] A more improved isogrid structure is known to be used for the solar array panel of MightySatII spacecraft (MightSat II Overview, http://www.vs afrl.af.mil/vsd/MightySatII/index.html).

Recently, innovative manufacturing techniques were developed[2,3] for the composite isogrid structures and the grid structure is drawing engineer's attention again. Chen and Tsai[4] proposed an analytical approach suitable for the analysis of the composite grid structures. Other proceeding papers[5,6] have shown that the composite grid structure can be widely used for civil infrastructure applications.

In previous studies[1,4–6] it has been shown that composite grid structure can provide high specific stiffness and strength as well as good damage tolerance and other advantages. With these advantages composite grids have various potentials to be applied to aerospace structures.

The present paper proposes a cost-saving technique for the design and manufacturing of a carbon/epoxy square grid with near-zero CTEs in the three geometrical principal directions. Detail manufacturing procedure of the grid structure is explained in the following section. Results of experiment and numerical simulation are also provided to demonstrate the superior performance of the proposed carbon/epoxy square grid structure.

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*Professor, Department of Aerospace Engineering. Member AIAA.
†Associate Professor, Department of Aerospace Engineering. Member AIAA.
‡Graduate Student, Department of Aerospace Engineering.

Manufacturing of Carbon/Epoxy Square Grid Structure

The proposed composite square grid structure is composed of slotted joint ribs and square tubes as shown in Fig. 1. The rib-1 and rib-2 are assembled perpendicularly by matching the slots of ribs. A sliced square tube is then inserted through the empty space surrounded by four sides of ribs. Therefore, thickness of the "wall" inside the composite grid structure is the sum of thickness of two tubes and one rib. One remaining problem is how to bond the ribs and tubes together. The process must be designed so that the final composite grid structure has sufficient bonding strength. At the same time the bonding procedure should be simple enough to reduce manufacturing cost.

Because the proposed composite square grid structure is composed of slotted joint ribs and square tubes, uniform pressure is hard to apply to all of the bonding surfaces during the whole bonding process. In the present study an autoclave processing method using silicon rubber and metal tools has been developed. The metal tools, silicon rubber rod with square cross section, the tube after cure, and sliced tubes with silicon rubber are shown in Fig. 2.

To construct a square tube, the prepreg was wrapped around the square silicon rubber mandrel. The wrapped prepreg was placed in the aluminum bottom mold and enclosed by the top mold. The wrapped prepreg was cured at 127°C for three hours. Thermal expansion of the silicon rubber under the elevated temperature environment provides pressure to squeeze out surplus resin of the prepreg. After curing, the tube and silicon rubber rod were sliced together in the predesigned dimension. To make composite ribs, autoclave-processed laminates were cut in the appropriate dimension, and then slots were placed for the slotted joint as shown in Fig. 1. As the raw material for the ribs and tubes, the high-modulus carbon/epoxy prepreg (UPN 116B; SK Chemicals, Republic of Korea; $E_1 = 231.17$ GPa, $E_2 = 7.19$ GPa, $\nu_{12} = 0.29$, $\alpha_1 = -1.58 \times 10^{-6}$/°C, $\alpha_2 = 32.18 \times 10^{-6}$/°C) was chosen in consideration of stiffness and CTE.

After applying epoxy adhesive (CIBA GEIGY, Araldite AW 106) on the contacting surfaces of tubes and ribs, the grid was assembled and the assembly was cured in the autoclave. The thermal expansion of the silicon rubber provides bonding pressure to the contacting surfaces in this procedure. Figure 3 shows a sample of the cured 4 × 3 composite square grid structure with a one-sided face sheet.

Selection of Ply Layup for Composite Wall

The ply layups for the rib and the square tube were selected such that the resultant CTE of the wall would be near zero. Analysis using the CLT shows that the laminates with stacking sequences such as $[0/90]_S$, $[0/\pm 60]_S$, and $[0/\pm 45/90]_S$ have near-zero CTEs

Table 1 Comparison of elastic constants and CTEs for various grid walls

	Wall layup (tube layup) (rib layup)			
Parameter	$[0/90]_{3S}$ ($[0/90]_2$) ($[0/90]_S$)	$[0/\pm 60]_{3S}$ ($[0/\pm 60]_2$) ($[0/\pm 60]_S$)	$[(0/90)_2(0/\pm 60)]_S$ ($[0/90]_2$) ($[0/\pm 60]_S$)	Al 2024-T4
$\alpha_x = \alpha_y = \alpha_z$ ($\times 10^{-6}$/°C)	−0.29	−0.29	−0.29	23.2
$E_x = E_y = E_z$, GPa	119.45	82.9	106.1	73.0
$G_{xz} = G_{yz}$, GPa	4.28	31.5	15.9	28.5
Density, kg/m^3	1600	1600	1600	2800

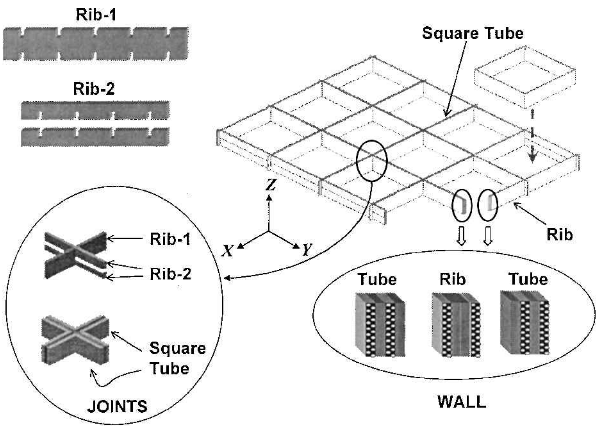

Fig. 1 Assembly of the carbon/epoxy square grid structure.

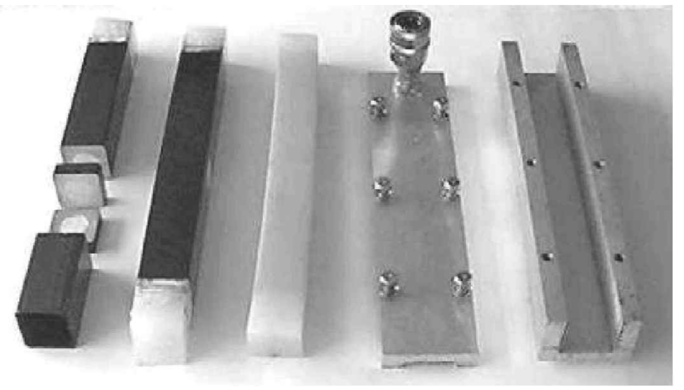

Fig. 2 Metal tools, silicon rubber rod, a tube after cure, and sliced tubes (from right).

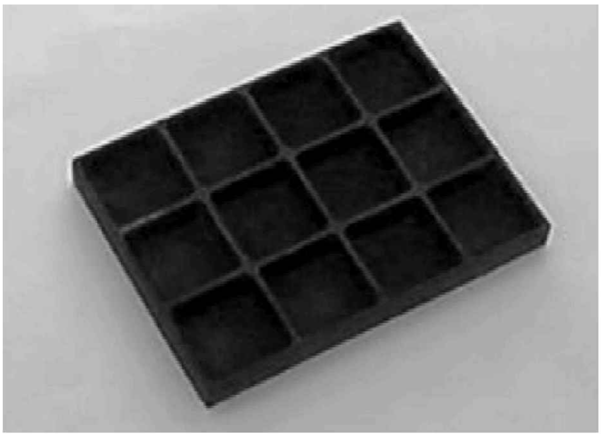

Fig. 3 Composite grid structure (20 × 15 cm).

($\alpha_x = \alpha_y = -0.29 \times 10^{-6}$/°C) in the in-plane directions. The layups of [0/90] and [0/±60] were selected as basic stacking sequences for the square tubes and ribs of the gird structure in the present study. The walls of grid structure with these ply orientations become quasi-isotropic in the x–z plane and in the y–z plane of the grid, when the square tubes and the ribs are bonded together. This means that the designed grid structure can have near-zero CTEs in the x, y and z directions.

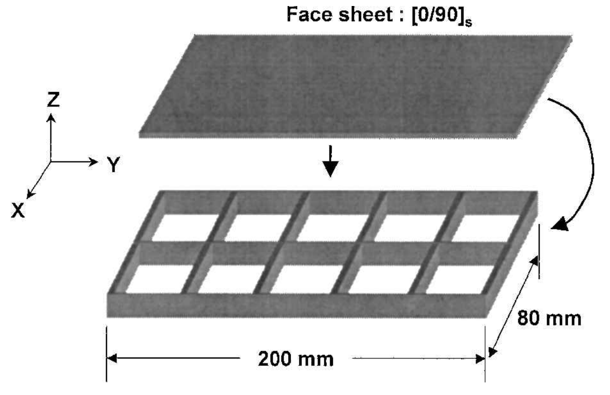

Fig. 4 The 5 × 2 grid structure.

The results of the analysis using the CLT (Table 1) show that laminates with [0/90] and [0/±60] stacking sequences have near-zero CTEs not only in the x and y direction but also in the z direction, i.e., through-the-thickness direction. The near-zero CTE in the thickness direction is quite a different characteristic from that of the conventional sandwich structures. This feature is very important for the structures requiring extremely high stability in thermal distortion, such as parabolic antennas and solar panels of a satellite structure. Equivalent elastic constants are also summarized in Table 1 for comparison.

Finite Element Analysis of Grid Structures

Numerical examples are provided in this section to demonstrate the superior performance of the composite square grid structures. MSC/NASTRAN is used for the finite element analysis, and the four-node QUAD4 elements are used to model 5 × 2 grid structures with two-sided face sheets shown in Fig. 4. Face sheets are bonded at the top and bottom of the grid in this example. For comparison, a virtual aluminum grid structure with the same geometry is modeled in the same way.

As the first example, the three-point bending experiments of the two composite grid structures are numerically analyzed. Only a quarter of the grid structure is modeled for analysis because of the symmetry in geometry and loading condition. Table 2 summarizes results from the finite element analysis. The maximum vertical displacement of the composite grid structure with the wall ply orientation of $[0/90]_{3S}$ is about 2.1 mm, and that of the grid structure with wall ply orientation of $[(0/90)_2(0/\pm 60)]_S$ is about 1.5 mm for a total central load of 1000(N). When these two grid structures are made of aluminum, the maximum vertical deflections are 1.8 and 1.7 mm, respectively, for the same loading condition.

From this numerical example we can see that weight of the composite grid structure with $[(0/90)_2(0/\pm 60)]_S$ is 43% less than that of the aluminum grid structure with the same geometry, whereas the composite grid structure with $[(0/90)_2/(0/\pm 60)]_S$ wall is more stiff than the aluminum grid structure. Figure 5 shows the deformed shapes and vertical deflections of the composite grid structures with $[(0/90)_2(0/\pm 60)]_S$ wall and the aluminum grid structure for the total central load of 1000(N).

The following example may be more impressive. The composite and aluminum grid structures are now under free thermal expansion. Temperatures of 125 and 25°C are prescribed on the top and bottom face sheets, respectively. A temperature of 75°C is assigned at the grid points on the vertical wall of grid structures.

Figure 6 represents the deformed shape and vertical deflection of each grid structure. The thermally induced vertical displacement of

Table 2 Comparison of maximum vertical displacement (three-point bending)

	Carbon/epoxy grid			Aluminum grid	
Ply orientation	Wall thickness, mm	Weight, g	Maximum displacement, mm	Weight, g	Maximum displacement, mm
$[0/90]_{3S}$	$t = 1.2$	40.9	2.1	70.2	1.8
$[(0/90)_2/0/\pm 60]_S$	$t = 1.4$	44.2	1.5	77.4	1.7

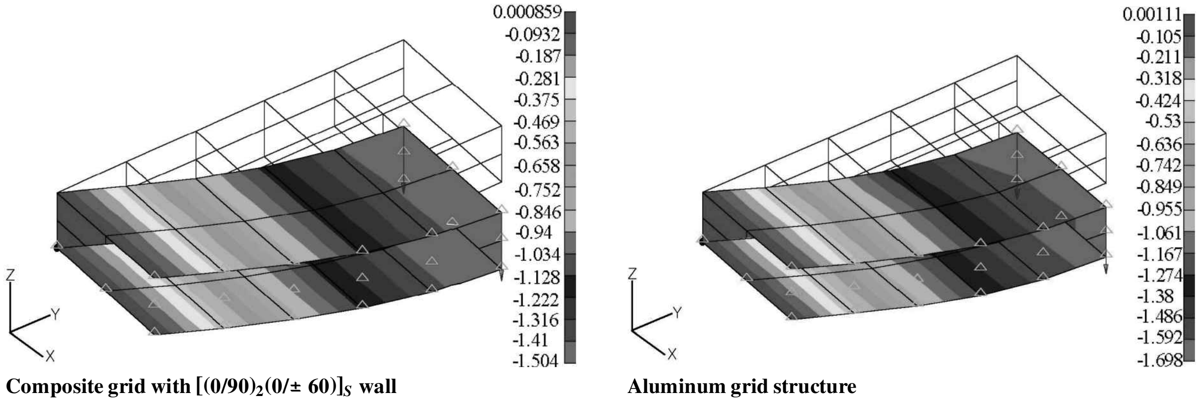

Fig. 5 Finite element analysis: three-point bending of 5 × 2 grid structures.

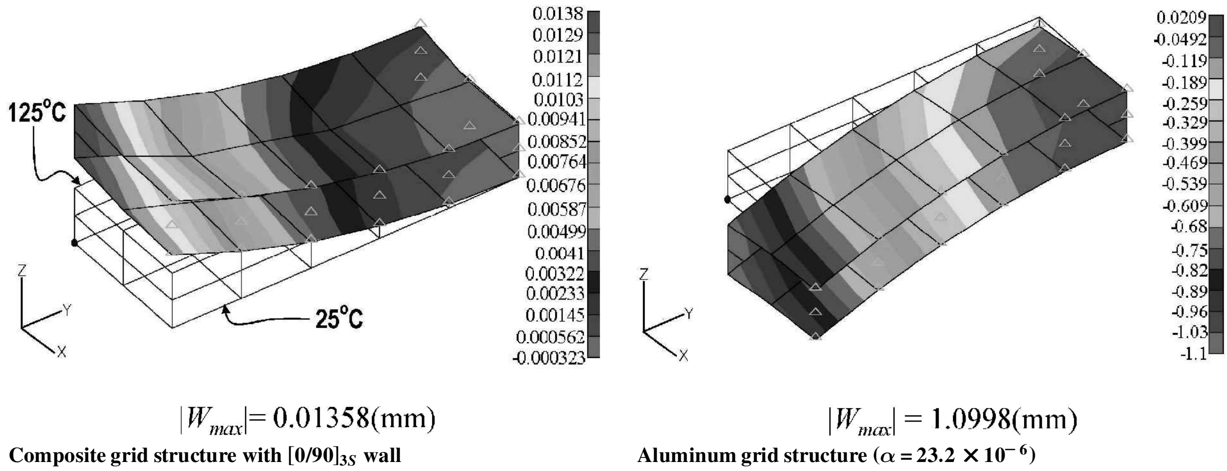

Fig. 6 Finite element analysis: thermally induced deflections of 5 × 2 grid structures.

the composite grid structure is about 1.3% of the vertical deformation of the aluminum grid structure with the same geometry.

Thermal Distortion Test

A thermal distortion test was conducted to compare the thermally induced deformation of the present carbon grid structure and the aluminum honeycomb sandwich panel with similar dimension. To measure the thermally induced deflection of the specimens, a simple deflection measuring system was constructed for only rough comparison. The system consisted of a heater with quartz heating elements, temperature-sensing thermocouples, and dial gauges, as shown in Fig. 7. To prescribe a significant temperature difference between the upper and lower surface of a specimen during the test, the lower face of the specimen was placed 100 mm above the quartz heating elements. Insulating panels were guided around the four sides of the specimen to prevent the heat convection from the heater to the upper face of the specimen.

After turning on the quartz heaters, displacements at the three measuring points on the upper face of each specimen were measured using dial gauges, and the temperatures of the upper and the lower surfaces were measured simultaneously at every 10 s until the temperature of the lower surface reached 150°C. The specimens were a 200 × 80 × 12.35 mm carbon/epoxy composite grid structure manufactured in this study and a 200 × 80 × 11 mm aluminum face/aluminum honeycomb core sandwich panel (face sheet thickness: 0.5 mm, aluminum honeycomb core: Hexcel HRH 10-1/8-5.0, total thickness: 11 mm). Because of manufacturing cost and manufacturing equipment problem, the aluminum sandwich panel with aluminum grid core could not be prepared.

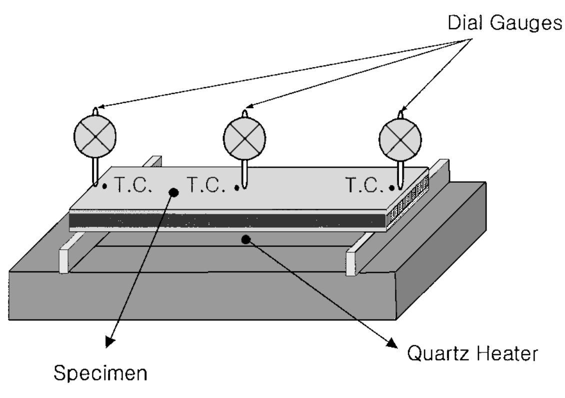

Fig. 7 Schematic of thermal distortion test system.

The measured thermal deflection data for about 100°C temperature difference between the upper and the lower surfaces are compared here: for the $[0/90]_{3S}$ carbon/epoxy grid structure the weight is 40.9 g, and the center deflection is 0.11 mm; and for the aluminum sandwich the weight is 58.0 g, and the center deflection is 1.0 mm. We can see the measured center displacement of the carbon/epoxy grid sandwich is about 11% of the displacement of the aluminum sandwich panel. According to the preceding numerical analysis, the thermally induced deflection of carbon/epoxy grid sandwich panel under 100°C temperature difference should be much less than the measured deflection. This discrepancy may come from the limited accuracy of the deformation measuring equipment. For further verification of thermal stability of carbon/epoxy grid panel, more accurate displacement measuring equipment, such as noncontact laser displacement system with a very stable supporting jig, must be used.

Conclusions

In this paper, design and manufacturing techniques are proposed for the construction of a composite grid structure. Ply orientations of the rib and tube are selected such that each member has near-zero in-plane CTE. Therefore, the resulting composite grid structure has near-zero CTEs in the three-dimensional directions.

Performance of the proposed composite grid structure is demonstrated by experiment and a finite element analysis. In the experiment thermally induced vertical deflection of the composite grid structure was much less than that of the aluminum honeycomb sandwich structure with similar dimension. From the finite element analysis it is confirmed that the thermally induced deflection of the designed composite grid structure is near zero and the bending stiffness is higher than that of the aluminum grid structure with the same geometry.

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A. M. Wass
Associate Editor