Thermal shape change of some CFRP-aluminum honeycomb sandwiched structures

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ABSTRACT

Carbon fiber reinforced plastic (CFRP) is a suitable material for space and ground-based telescope structures. CFRP has a high stiffness-over-weight ratio and a low thermal expansion coefficient. Together with aluminum honeycomb, CFRP can form very strong light-weight sandwiched structures. These sandwiched structures, which can support high bending moments and shear forces without much deformation, are used widely in the existing and future large-space or ground-based telescopes. However, some special CFRP-aluminum honeycomb sandwiched structures have shape change problems when the absolute temperature changes. In this paper, some of these thermal shape changes are discussed. The designers of the future large telescopes should be fully aware of the shape change problem of these structures.

Keywords: Carbon fiber, composite, thermal deformation

1. INTRODUCTION

A sandwiched structure is a highly efficient composite structure. Its top and bottom surfaces are made of high performance materials, while its middle cores are made of light weight material such as aluminum honeycomb or plastic foam. When an outside load is applied to sandwiched structures, the top and bottom surfaces will undergo tension and compression, while the middle core will only produce shear strain. A CFRP plate has a very high tensile modulus, and aluminum honeycomb is very light in weight. CFRP-aluminum honeycomb sandwiched structures have been widely used in aerospace and other industries. The bending stiffness of a sandwiched structure is:

$$D = \frac{1}{3}\left[\frac{2E_f}{1-\nu_f^2}\left(\frac{3}{4}h_c^2 t_f + \frac{3}{2}h_c t_f^2 + t_f^3\right) + \frac{E_c}{1-\nu_c^2}\frac{h_c^3}{4}\right] \tag{1}$$

where E_f and E_c are the Young's moduli of the surface plate material and the core material; ν_f and ν_c are their Poisson's ratios; t_f and t_c are the thickness of one surface layer and the core in between. Since $E_f >> E_c$ and $t_f << h_c$, therefore equation (1) could be reduced as:

$$D = \frac{1}{2}\frac{E_f h_c^2 t_f}{1-\nu_f^2} \tag{2}$$

Comparing equation (2) with the formula for the bending stiffness of a solid plate, one could find that the stiffness of the sandwiched plate is much higher than that of a solid plate with the same weight. For carbon fibers, their coefficient of thermal expansion (CTE) is very low and is usually a negative number. CFRP laminate plates with their fibers in different directions also have a low CTE number. From the strength of material approach, the in-plane CTE of a sandwiched plate is[2]:

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$$\alpha = \frac{2\alpha_f E_f t_f + \alpha_c E_c h_c}{2E_f t_f + E_c h_c} \tag{3}$$

where α_f and α_c are CTEs of the top and bottom CFRP surface plates and the core material respectively. The resulting in-plane CTE in the sandwiched plate is also low. However, in the out-plane direction, the expansion of the sandwiched plate is determined by the expansion of the core material. The CTE in this direction is usually larger.

From this analysis, it can be found that the CFRP-aluminum honeycomb sandwiched structures are thermally anisotropic. Even for a sandwiched flat plate, the in-plane and out-plane CTEs are different. For other shaped structures, the thermal deformation is even more complex. This is a major problem when CFRP-aluminum honeycomb sandwiched structures are used in the precision optical, infrared or millimeter wavelength telescopes. This paper will discuss in detail thermal shape changes of some typical sandwiched CFRP-aluminum honeycomb structures. These include thin box-shape, thin wall cylinder shape, T-shape, L-shaped and channel-shaped structures.

2. THIN BOX-SHAPE SANDWICHED STRUCTURES

Some millimeter wavelength antennas use CFRP-aluminum honeycomb sandwiched surface panels. These panels have their top and bottom surfaces made of CFRP plates. However, their side edges are made of high CTE plastic. With temperature changes, the side edges expand nearly the same as aluminum honeycomb. There is no edge effect on the top and bottom surfaces. The surface shape will remain unchanged. If all the side edges are made of low CTE CFRP plates, the side edges will expand much less than the aluminum honeycomb. The top and bottom surfaces of the box will bow outwards as the temperature of the structure increases. The thickness difference between the center and the edge is:

$$\delta h = h_c(\alpha_c - \alpha_f)\Delta t \tag{4}$$

where Δt is the temperature change in degrees. Since both top and bottom plates bow outwards, the side plates may be affected as well. All the surfaces of the structure are not suitable for optical bench purposes. This will be the same for a thin-walled cylinder shape CFRP-aluminum sandwiched structure. The overall shape change or the surface slopes of these structures depend on their dimensions. When the dimension ratio of the adjacent two sides of the box or the cylinder ring is large, the overall shape change will be smaller.

3. T-SHAPE SANDWICHED STRUCTURES

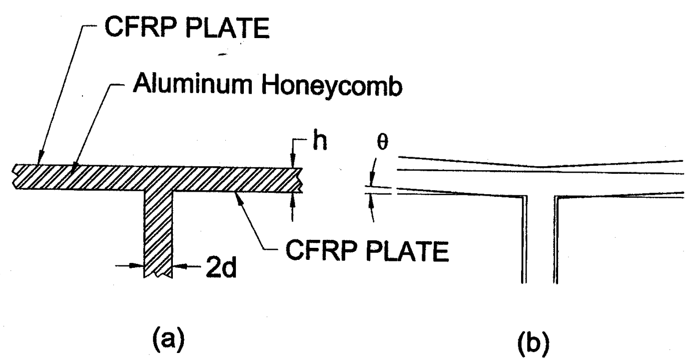

Figure 1: (a) The T-shaped sandwiched structure and (b) its thermal shape change (Cheng,2003)

For a T-shaped structure (cross-section is as in Figure 1(a)), if all the side surfaces are made of CFRP plates and the core is made of aluminum honeycomb, then any temperature change will produce a shape change as well. Considering the two parallel lines on both sides of the horizontal sandwiched plate, the top line is made of CFRP plate where the CTE is nearly zero; the bottom line is not made of the same lower CTE material. There is a small length of $2d$ being made of high CTE aluminum honeycomb. When the temperature changes, lengths of the top line and the bottom line will be different by a small amount of:

$$2\Delta d = 2d(\alpha_c - \alpha_f)\Delta t \qquad (5)$$

To accommodate this length difference between the top and the bottom lines, the horizontal part of the T-shaped structure has to bend upwards or downwards. When the temperature increases, the horizontal part will bend upwards as shown in Figure 1(b). If the height of the horizontal part is h, then the angle of the bending will be:

$$\theta = \Delta d / h = d(\alpha_c - \alpha_f)\Delta t \qquad (6)$$

This shape change is significant if the structure is used as an optical bench. In this section, we have not mentioned the thickness change of the horizontal part of the T-shaped structure. The changed amount is $\Delta h = h(\alpha_c - \alpha_f)\Delta t$.

4. L-SHAPE SANDWICHED STRUCTURES

A right-angled structure is also called an L-shaped structure (Figure 2(a)). The L-shape is exactly half of a T-shaped structure. If the skins of the L-shaped structure are all made of CFRP plates, the first order approximation of the thermal deformation will ignore the thickness change of the horizontal part. The analysis will be the same as that of a T-shaped structure. If the vertical part of the structure remains vertical, the horizontal part will bend upwards when the temperature increases. The calculated angle change of the L-shaped structure is (ref. Figure 2(b)):

$$\theta = d(\alpha_c - \alpha_f)\Delta t / h \qquad (7)$$

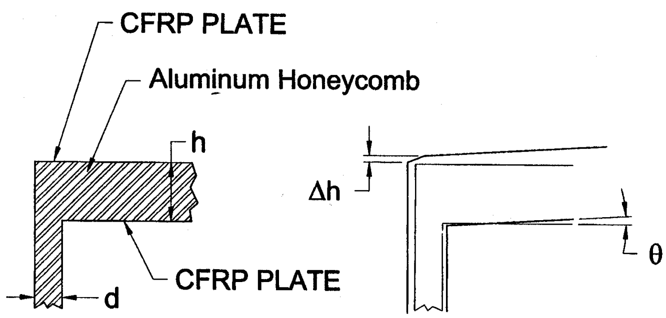

Figure 2: (a) The L-shaped sandwiched structure and (b) its thermal shape change (Cheng,2003)

When $h > d$, the first order approximation gives a good estimation of the angle changed. The major assumption of the first order approximation is that the corner A remains a right angle (Figure3(a) and (b)). However, this first order approximation has a problem. For the same L-shaped structure, either side could be seen as the horizontal part. In Figure 3(a), the angle θ_1 is the same as θ in equation (7). If the thickness h of the horizontal plate is now replaced by the thickness d of the vertical section as in Figure 3(b), the resultant angular change would be (Figure 3(b)):

$$\theta_2 = h(\alpha_c - \alpha_f)\Delta t / d \qquad (8)$$

The angles of θ_1 and θ_2 are not the same if the dimensions of d and h are not the same. Therefore, errors exist in this approximation. The reason for this error could be found from Figure 2(b). After the temperature increases, the top surface is lifted up by a small amount $\Delta h = h(\alpha_c - \alpha_f)\Delta t$. The edge AB and edge AD in Figure 3(a) and (b) are no longer perpendicular to each other when the temperature changes. At the same time, when the angle change θ_1 is calculated, the edge AD has been pulled to the right side, while the edge AB would be pulled downwards by a small amount. This effect can be found from the finite element analysis. In the first approximation, if $h = d$, then $\theta_1 = \theta_2$. The first order approximation gives the range of the angle change. The range is set by both angle θ_1 and θ_2 . By using this first order approximation, either the θ_1 value or the θ_2 value could be used; it would be wrong to add these two angles together. When $h = d$, the first order approximation gives an upper limit of the deformation. When $h > d$, then θ_1 value gives a better, but smaller, estimation of the angle changed.

For a better estimation of the angle change, a second order approximation is necessary. In the second order approximation, angle A will not remain a right angle after the temperature changes as shown in Figure 3(c). However in this approximation, both angles B and D still remain right angles after the temperature changes. This assumption agrees with the small deformation theory of the thermal expansion. In the same time, both edges BC and CD have been expanded to an exact amount when the temperature changes. The angular change θ of this second order approximation is:

$$\theta = \frac{\pi}{2} - arctan(\frac{d}{h + \Delta h}) - arctan(\frac{h}{d + \Delta d}) \quad (8)$$

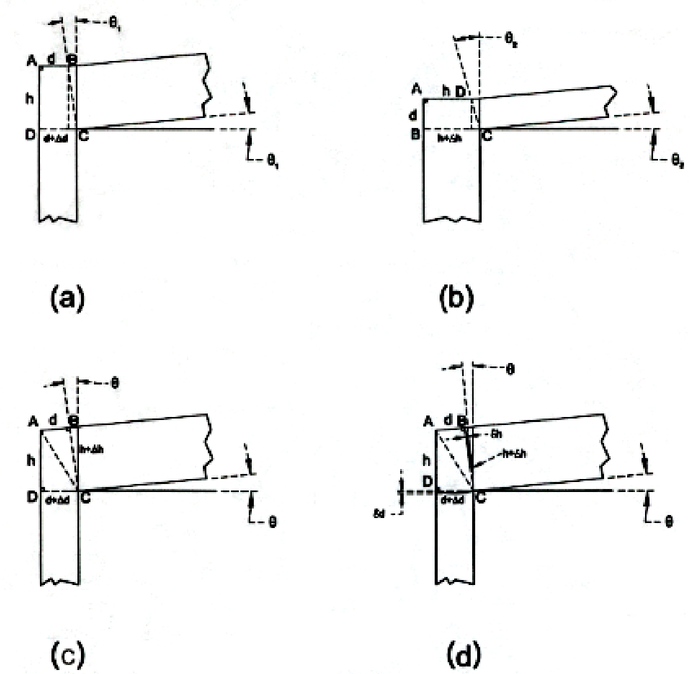

Figure 3: (a) Case 1 of the first order approximation, (b) case 2 of the first order approximation, (c) the second order approximation and (d) a more accurate approximation of the L-shaped thermal deformation (Cheng, 2003).

where $\Delta d = d(\alpha_c - \alpha_f)\Delta t$. This second order approximation is close to the real angle change of the L-shaped structure. However, a more accurate approximation should consider the bending of both BC and CD edges (ref Figure 3(d)). This could be found from the area expansion after the temperature increases. In Figure 3(c), the area of ABCD after temperature change is $d \cdot h[1 + (\alpha_c - \alpha_f)\Delta t]$. This number is smaller than the free area expansion result of $d \cdot h[1 + (\alpha_c - \alpha_f)\Delta t]^2$. Therefore, both edges BC and CD may bend outwards to accommodate this area expansion. The exact result of this angle change could be calculated by balancing the internal forces of each smaller area of this section. The formulation of this further approximation is not so easy to derive. The best prediction of the angle change can be calculated through the finite element analysis.

5. CHANNEL-SHAPE SANDWICHED STRUCTURES

A channel-shaped sandwiched structure is shown in Figure 4(a). Thermal expansion of this structure will also change its shape. If both vertical parts of the structure are constrained, the thermal deformation will bend the top surface when the temperature changes as shown in Figure 4(b). The radius of curvature of this bending is:

$$R = \frac{\sqrt{1+\theta^2} * D}{2\theta} \tag{9}$$

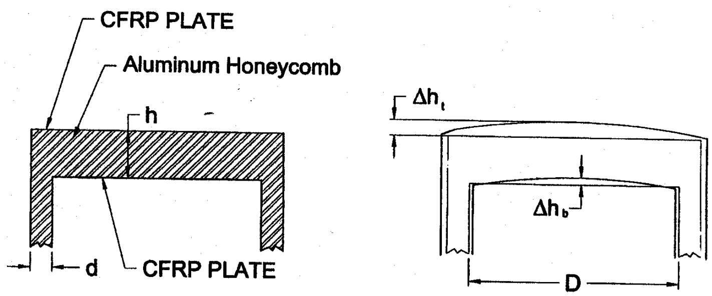

Figure 4: (a) The channel-shaped sandwiched structure and (b) its thermal shape change (Cheng,2003)

where θ is the angle change of one corner as discussed in the previous section. From equation (9), the maximum height changes for the lower and the upper sides of the top plate are:

$$\begin{aligned} \Delta h_b &= R - R\cos\theta \\ \Delta h_t &= \Delta h_b + h(\alpha_c - \alpha_f)\Delta t \end{aligned} \tag{10}$$

Equation (10) shows that the bottom side deformation is smaller than that of the top side. For this shaped structure, if the constraints on both vertical parts are removed, the top surface could remain flat when the temperature changes. At this time, the vertical parts will open up or close inwards.

6. COMPUTER ANALYSIS RESULTS

In the above analysis, the bending stiffness of the CFRP skin is ignored (It is in fact small.). To include the effect of skin stiffness, finite element computer models for both the L-shaped and channel-shaped structures are built. In the computer models, the moduli for skin and core are typical numbers as: $E_f = 150GPa$, $E_c \approx 210MPa$ (For aluminum honeycomb, the moduli in the L and W directions calculated are $\frac{3t_c E_{al}}{10d_c}$ and $\frac{t_c d_c E_{al}}{3{l_c}^2}$ respectively, where E_{al} is the modulus of aluminum, $d_c = 0.866 l_c$, l_c is the side length of the hexagonal core, and t_c is the thickness of the core skin. In the other direction, the modulus is equal to $\frac{4t_c E_{al}}{3d_c}$). For the L-shaped sandwiched section if $d/h = 0.3$, the angle change after finite element analysis is about $2.26 arc\,min$ for a 20-degree temperature change. For a channel-shaped sandwiched section with the same d / h ratio and $D = 1m$, the maximum deformation of the top plate is about $56\mu m$ for a 20 degree temperature difference. These results agree well with the approximation formulas in this paper.

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