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THERMALLY ADAPTIVE BUILDING COVERINGS: THEORY AND APPLICATION

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ABSTRACT

The paper begins with a brief overview of historical building coverings. Thermadapt™ thermally adaptive buildings are introduced as a completely new class of shingles, siding and roofing. These elements physically change shape in response to thermal loading. In hot weather with high solar loading, the panels curl up and away from the building. As the temperature cools and the sun sets, the Thermadapt™ elements lie close to the building. In cool temperatures, the elements lie flat agains the building transferring solar energy. In extremely cold temperatures, high convexity inherently forms in the elements, forming a pocket of trapped dead air which forms a highly effective layer of insulation. Thermadapt™ elements are analytically modeled using Classical Laminated Plate Theory (CLPT). Although Thermadapt™ elements may use materials like shape memory alloys, cost concerns drive the use of coefficient of thermal expansion mismatch as the basic driving mechanism. A series of experiments were performed on a variety of Thermadapt™ elements using high CTE mismatch pairs of structural materials including graphite-epoxy and aluminum and Invar and aluminum pairings. Analytical estimates are shown to predict the performance of the Thermadapt™ panels with great accuracy with curvature levels measured and predicted in excess of 5 deg/m/°C. Analytical predictions using CLPT employed a lateral constraint, driving lateral curvature, κ_y, to zero by the use of stiff lateral constraint mechanisms like edge rolls and lateral corrugations. This constraint was shown to increase deflections by roughly 33% over the unconstrained elements which were simply allowed to encounter equal curvatures in x and y directions, or "doming."

NOMENCLATURE

A	extensional stiffness matrix	N/m (lbf/in)
B	coupling stiffness matrix	N/m (lbf/in)
d	linear tip deflection of test element	mm (in)
D	bending stiffness matrix	N-m^2/m (in^2-lbf)
E	extensional stiffness	Pa (psi)
EI	bending stiffness	N-m^2 (lbf-in^2)
G	shear modulus	Pa (psi)
L	length	mm (in)
N	force per unit width of laminate	N/m (lbf/in)
M	moment per unit laminate width	N-m/m (in-lbf/in)
t	thickness	mm (in)
T	temperature	°C (°F)
u, v, w	deflections in the x, y and z directions	mm (in)
x, y, z	principal ply and laminate directions	~

Greek Symbols

α	coefficient of thermal expansion	µstrain/°C (µstr/°F)
ε	strain	~
σ	stress	Pa (psi)

Subscripts

bond	relating to the bond or adhesive layer
eff	effective
foam	relating to the backing foam
L	longitudinal
o	original
T	transverse
x, y, z	along the ply x, y, z directions
1, 2, 3	along the laminate 1, 2, 3 directions

Acronyms

CTE	coefficient of thermal expansion	µstrain/°C(µstr/°F)
OR	orthotropy ratio	
SMA	shape memory alloy	
SR	stiffness ratio = E_1/E_2	
TF	test facility	
TR	thickness ratio = t_1/t_2	

INTRODUCTION

The field of thermally adaptive building coverings is at once new and old. If one examines roofing materials like thatch, it is easy to see that in a way, it is adaptive: cooling effects in hot weather are well matched to effective warming effects in low temperatures. With that said, this paper is centered on mechanical thermal adaptivity of building coverings like shingles, siding and roofing. Conceived in 2009, these coverings have been methodically explored behind closed doors for the past seven years.

1.1. Historical Building Coverings

Building coverings of many kinds have been used by humans since the first leaves and branches were leaned against stick-shelters erected by prehistoric hominids. Since that time, materials like thatch, reed, cloth, bamboo, clay, slate, copper, aluminium, steel, tin, asphalt, plastic, concrete, sod and others have been used to shield buildings and the people therein from the elements. Although quite effective, they have one overarching characteristic in common: Their shapes remain essentially unchanged from season to season, day to night, hot to cold. Outside of the linear expansion and contraction of items like long runs of siding, they are basically fixed as seen in Figure 1.

Figure 1 Conventional Building Coverings

Clearly, building coverings have made use of many many different kinds of materials through the ages. With that said, there appears to be scant few if any examples of building coverings that are capable of actively changing their shape.

1.2. Adaptive Structures

Although the field of man-made "adaptive," "smart," and/or "intelligent" structures may seem new, it is actually quite old and draws its roots to the 1800's when Jacques and Pierre Curie (the fabled Nobel Laureate of 1903), performed experiments on Rochelle salts.[1-3] Similarly, the properties of the first shape-memory alloys also date to that time.[4,5] In modern times, so many technologists have investigated these "adaptive" structures that a plethora of books, conferences and journals abound.[6-11] Some adaptive structures, substructures and device technologies have been accepted for so long that not only are they in entire fleets of aircraft like the F-14, but that fleet is so old that it is now retired. Many other branches of technology like the Aerospace industry now consider them to be standard actuators for many applications as shown in the collage below showing a small sampling of adaptive aerostructures.[10-13]

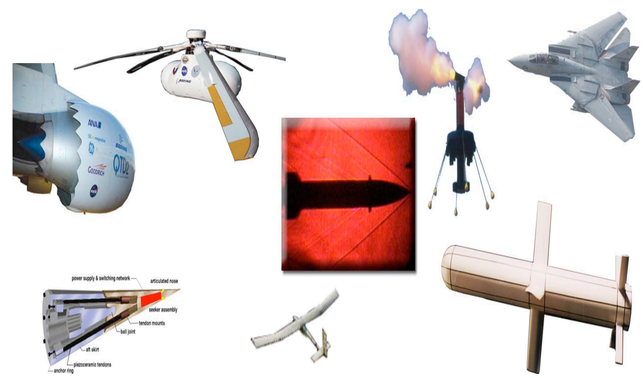

Figure 2 Sample of Aerospace Systems and Aircraft which have used Adaptive Structures in the Past 20 Years[10-13]

The field of thermally adaptive building coverings is quite new in that the patent filings underpinning the field are just a few months old.[14,15] The first conference publication dates to May of 2016.[16] This first publication showed that Thermadapt™ thermally adaptive building coverings were exceptionally effective at protecting the building from the elements. Indeed, a series of tests on full-scale buildings were conducted. One building was fitted with Thermadapt™ siding and roofing. A second building was fitted with conventional insulation. A third was used as a control. Testing showed that 1cm (3/8") thick Thermadapt™ panels achieved the same level of thermal insulation as R33 worth of insulation. Data was gathered at a rate of one sample a minute for a full calendar year at five identical locations in each building. Testing indicated that Thermadapt™ panels achieve an equivalent thickness normalized R-value of more than 100/inch. These Thermadapt™ panels were highly effective in all temperature ranges and showed no functional degradation over five years of continuous environmental exposure at the Holden, Missouri Outdoor Test Range as seen in Figure 3.

Figure 3 Three Outdoor Test Facilities (TF) of Ref. 16

As can be seen in Ref. 16, the Outdoor Test Range data was methodically gathered over an entire year. Test Facility 2 was fitted, retrofitted and retrofitted with ever-increasing levels of thermal insulation till the interior centroid temperatures matched. At that point, it was determined that the particular level of insulation in Test Facility 2 was a match to the performance of the Thermadapt™ equipped Test Facility 1. Figure 4 shows the outstanding temperature tracking of the Test Facilities 1 and 2 (black and light green lines).[16]

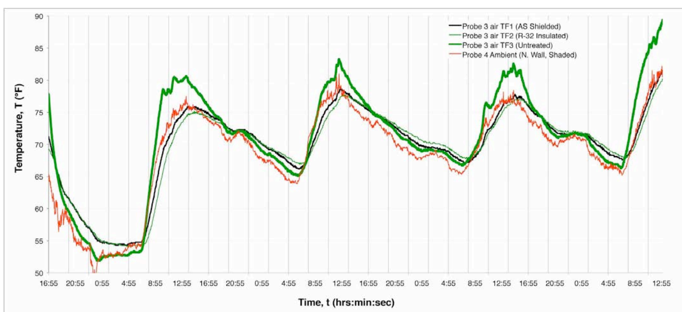

Figure 4 Test Range Data showing Tracking of Thermadapt™ Equipped Building and Building Insulated to R33 (Ref. 16)

Modeling

The primary modeling method used to capture the performance of Thermadapt™ elements is Classical Laminated Plate Theory (CLPT). There are typically four major layers of material making up Thermadapt™ elements. The first layer is an outer structural layer. This outer layer has a lower coefficient of thermal expansion (CTE) than the other layers. Underneath this low CTE layer is a bond layer. This layer may have a fibrous inner core or not. Often this layer is fundamentally rigid, but it does not have to be. The inner structural layer typically has a much higher CTE than any other layer. Lying inside of these three layers is an inner insulation/reflection layer. This radiant barrier layer is critical for maintenance of good performance of the Thermadapt™ building covering as it is an outstanding way to prevent excessive heat from solar loading from radiating towards the building inner covering and rain barriers. Often there is a non-structural, cosmetic layer applied to the outside of the low CTE layer to allow for customer acceptance. Figure 5 shows a typical Thermadapt™ element.

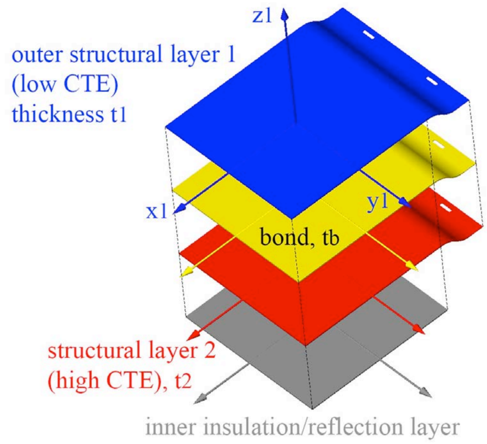

Figure 5 General Configuration of a Thermadapt™ Element

By using the modeling techniques and methods of Reference 17, the performance of the Thermadapt™ elements can be captured. Figure 6 shows the general conventions of the Thermadapt™ elements, again, modeled on Ref. 17.

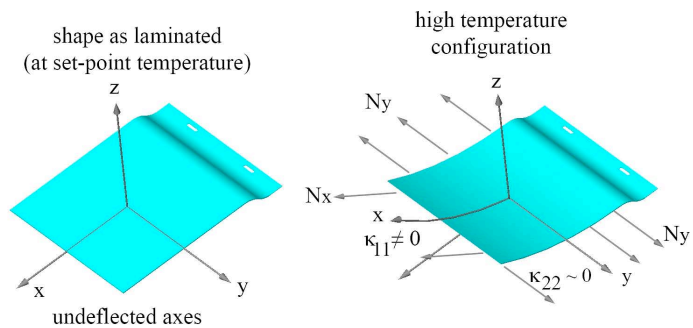

Figure 6 CLPT Modeling Conventions for Thermadapt™ Sheets

The reader will note that there are typically spanwise corrugations in Thermadapt™ elements. These corrugations typically increase the bending moment of inertia along the y-axis by one or more orders of magnitude. This has the effect of dramatically stiffening the element laterally so that the lateral curvature will typically be driven very close to zero. If one assumes that the lateral curvature is identically zero and neither shear nor twist results, a laminate plate theory expression may be derived for a so-constrained Thermadapt™ element in equation 1.

$$\begin{bmatrix} A_{11} & A_{12} & B_{11} \\ A_{12} & A_{22} & B_{12} \\ B_{11} & B_{12} & D_{11} \end{bmatrix}_1 \begin{bmatrix} (T-T_{ref})\alpha_{1x} \\ (T-T_{ref})\alpha_{1y} \\ 0 \end{bmatrix} + \begin{bmatrix} A_{11} & A_{12} & B_{11} \\ A_{12} & A_{22} & B_{12} \\ B_{11} & B_{12} & D_{11} \end{bmatrix}_2 \begin{bmatrix} (T-T_{ref})\alpha_{2x} \\ (T-T_{ref})\alpha_{2y} \\ 0 \end{bmatrix} +$$

$$= \begin{bmatrix} A_{11} & A_{12} & B_{11} \\ A_{12} & A_{22} & B_{12} \\ B_{11} & B_{12} & D_{11} \end{bmatrix}_L \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \kappa_x \end{bmatrix}$$

(eq. 1)

Through a series of algebraic substitutions, it can be seen that equation 1 can be expanded to an exact expression, neglecting the stiffness of the bond layer. One can see that equation 2 is very similar to the ubiquitous equation describing the doming curvature of an unconstrained bimetallic sandwich structure. The major difference is that the curvature is roughly 33% greater than the unconstrained variant.

$$\kappa_x \cong \frac{6E_1E_2\left(t_1+t_2\right)t_1t_2\left(1+\nu\right)\left(\alpha_2-\alpha_1\right)\left(T-T_{ref}\right)}{E_1^2t_1^4+E_1E_2\left(4t_1^3t_2+6t_1^2t_2^2+4t_1t_2^3\right)+E_2^2t_2^4} = \qquad \text{eq. 2}$$

If one normalized equation 2 with respect to stiffness and thicknesses of the two major structural components, then equation 2 devolves into a nearly nondimensional expression:

$$\kappa_x \cong \frac{6SR\left(TR+1\right)TR^2\left(1+\nu\right)\left(\alpha_2-\alpha_1\right)\left(T-T_{ref}\right)}{t_1\left(SR^2TR^4+SRTR\left(4TR^2+6TR+4\right)+1\right)} \qquad \text{eq. 3}$$

EXPERIMENTAL TEST ARTICLES

A series of nine laminated test specimens were fabricated to demonstrate the validity of the Thermadapt™ concepts. Specimens 1 – 8 were constructed from graphite-epoxy composite being used as the outer low CTE layer. Specimen 9 was constructed with Invar as the outer low CTE layer as seen in Figure 7.

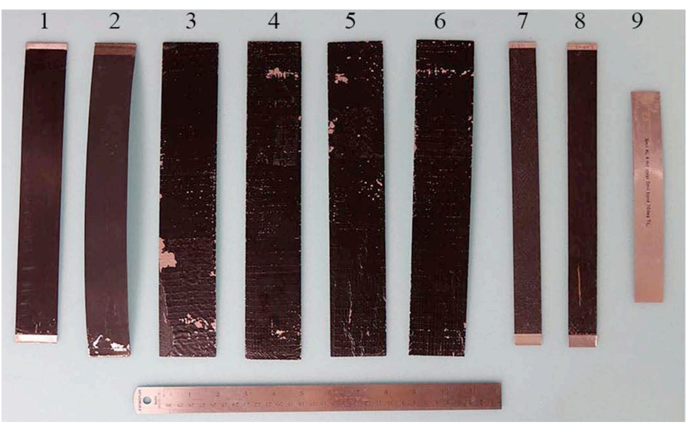

Fig. 7 Thermadapt™ Test Specimens

Figure 7 shows the nine test articles following testing and environmental exposure. As mentioned earlier, the amount of degradation in performance with environmental exposure of the fibrous, graphite-epoxy composite Thermadapt™ specimens was so small that it was under 0.2% per year. All of the specimens shown in Fig. 7 also underwent more than 300 freeze-thaw cycles over the many years of testing.

The geometries of the specimens shown in Fig. 7 represents a variety of fabrication techniques and materials. Table 1 shows the geometries of each specimen along with the material types of the structural components and the bond materials which were used. The denotation "9412" indicates the use of Hysol 9412 resin. The "GL" indicates a glass-filled variant.

	Specimen Number								
	1	2	3	4	5	6	7	8	9
Ltot (mm)	289	306	305	305	305	305	290	290	220
Leff (mm)	274	283	303	303	303	303	273	273	144
Weff (mm)	38	38	51	51	51	51	25.4	25.4	25.4
tlam (µm)	305	267	483	686	838	940	533	432	330
Standoff h (mm)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Bend h (mm)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Foam Type	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Foam Slots (mm)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Foam t (mm)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Aluminized foam	no	no	no	no	no	no	no	no	no
Mtl1 Type	PEEK	PEEK	GrUni	GrUni	GrUni	GrUni	GrUni	GrUni	Invar
t1 (µm)	203	178	203	203	203	203	305	203	102
E1eq (GPa)	67	67	63	63	63	63	52	52	145
α1 (µstr/°C)	2.5	2.5	2	2	2	2	2	2	1.2
Mtl2 Type	2024	321	2024	2024	2024	2024	2024	2024	2024
t2 (µm)	76	76	279	279	279	279	229	229	229
E2 (GPa)	70	200	70	70	70	70	70	70	70
α2 (µstra/°C)	23	17	23	23	23	23	23	23	23
Bond Material	9412	9412	9412	9412GL	9412GL	9412GL	9412	9412	9412
tb (µm)	25	13	0	203	356	457	0	0	0
Eb (GPa)	2	2	2	2	2	2	2	2	2
Date Fabricated	2/10	2/10	3/10	3/10	3/10	3/10	6/10	6/10	6/10

EXPERIMENTAL TESTING AND RESULTS

Laser reflection techniques as described references 13 and 18 were used to evaluate the performance of the Thermadapt™ elements. The test results indicated that very predictable levels of curvature with temperature could be achieved as shown in Fig. 8. To achieve uniform thermal loading on the element, all deflections were measured in a water bath ranging from 5 to 50°C.

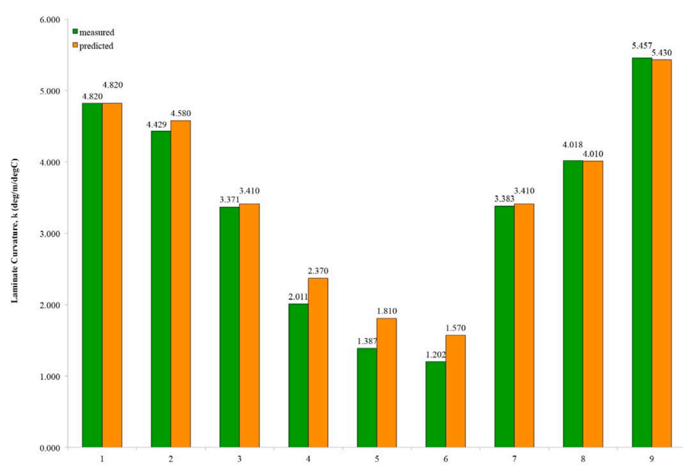

Fig. 8 Thermadapt™ Specimen Predicted and Measured Performance

Clearly from Fig. 8 it is obvious that theory and experiment line up quite well. Specimens 4 – 6 are also shown not to be as active as the other specimens which were tested. It is obvious that very thick bond layers retarded deflection performance. The reader should also note that while deflections of specimens 4 – 6 were lower than the rest, their bending stiffness levels were considerably higher than all other Thermadapt™ elements.

CONCLUSIONS

This paper has presented a new class of building covering which takes advantage of thermal expansion mismatch to curve away from the building face when exposed to high heat levels, and curves towards the building when cold, forming an insulating pocket of dead air. Classical laminate plate theory (CLPT) was shown to quite accurately predict the performance of the Thermadapt™ thermally adaptive elements. A series of nine Thermadapt™ elements were laid up with a low coefficient of thermal expansion (CTE) layer on the outside, followed by a bond layer and an inner layer of very high CTE. A variety of thicknesses were explored along with bond materials and structural combinations including graphite-epoxy and Invar being used in the outer, low CTE layers. Test results showed excellent correlation between theory and experiment with curvature levels ranging between 1 and 6 deg/m/°C and theory and experiment generally within 5% of theory, especially on the lamina with thin bond layers. Larger deviations between theory and experiment is seen on extremely thick specimens. This is most likely due to nonlinear finite-thickness related effects like shear lag and the active participation of the fiberglass in the bond line.

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