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Thermally adaptive building covering field test

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Abstract

This paper represents the first public exhibition of Thermadapt™ building coverings which were invented more than eight years ago. The paper starts with a brief overview of the field of adaptive materials and their applications in various industries. Thermally adaptive building covering sheet fundamentals are explained by laying out the basic structural mechanics of thermally induced gross shape changes in lamina. As a truncated paper, the driving theory, coupon, test chamber and subscale building data could not be included due to length constraints, but will be delivered during oral presentation. Nonetheless, data from outdoor range testing on three independent buildings is presented. These three buildings measuring 1.8m (6ft) deep x 2.4m (8ft) wide x 2.1m (7ft) high showed excellent results. The first was outfitted with Thermadapt™ siding and roofing. The second was outfitted with a variety of different amounts of insulation. The third was used as a control. The configuration of the full-scale test range buildings is shown along with performance data in all midwestern seasons. The data demonstrated that thin thermally adaptive building coverings are as effective as 27cm (10.5”) of fiberglass insulation, indicating an equivalent R-value of more than 40/cm (100/in). The paper concludes with an overview of the economics of Thermadapt™ building coverings and the intellectual property landscape.

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Keywords: Building Covering; Siding; Roofing; Shingles; Adaptive Materials; Smart Materials; Smart Structures; Smart Siding; Smart Shingles

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1. Introduction and Background

1.1. Historical Building Coverings

Building coverings of many kinds have been used by humans since the first leaves 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

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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 1.1.

Fig. 1.1 Typical Conventional Building Coverings

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 shape-memory alloys also date to that time.[4,5] In modern times, so many technologists have investigated these "adaptive" structures that books, conferences and journals abound.[6-11] Some adaptive components 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]

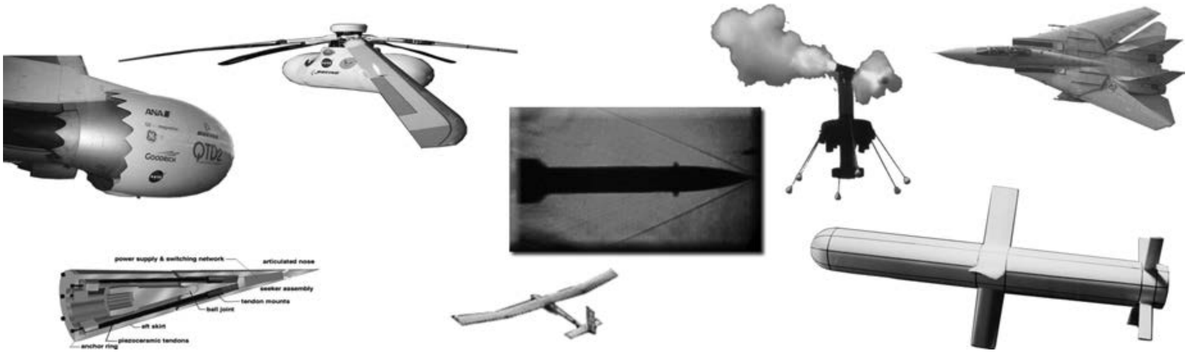


Fig. 1.2 Small Sampling of Aerospace Systems and Aircraft which have used Adaptive Structures in the Past 20 Years [10-13]

Although automotive, aerospace and medical device industries have embraced adaptive and smart structures, the world of civil engineering has yet to see widescale application. This comparatively slow pace of adoption is noted by authors like Del Grosso.[14] Even though Structural Health Monitoring with adaptive materials [15] is a subdiscipline of adaptive structures that is healthy, often involves civil structures and is an active branch of research, Del Grosso postulates that the major reason why adaptive materials have not been widely integrated into the civil infrastructure is because of challenges with control strategies.[14]

In spite of this control systems hurdle, some of the earliest and most successful applications of adaptive materials were made by Dry in the early 1990’s on self-healing concrete structures, which was followed by a bulk of research on self-healing composites.[16-24] As such, the control strategy associated with self-healing structures generally involves sensing the presence of a crack and appropriately responding with injection and cure of a variety of resins. Although a nontrivial challenge, a number of technologists have handily conceived of and demonstrated schemes to make this happen. Even with these considerable successes, the world of adaptive and smart materials is still comparatively underrepresented in civil engineering and architecture. Indeed, the most common types of adaptive materials that exhibit gross shape changes (like shape-memory-alloys) appear to be scarce at best in civil infrastructure research efforts and even more-so in application.

1.3. Fundamentals of Thermally Adaptive Building Coverings

One of the most daunting conditions a building can be exposed to is a combination of high heat and high solar radiation levels. This often occurs in desert climates and dramatically drives energy consumption up during the day as seen in Figure 1.3. It is estimated that air conditioning makes up 70 – 80% of electrical energy consumption in climates like the one that generated Fig. 1.3.[25]

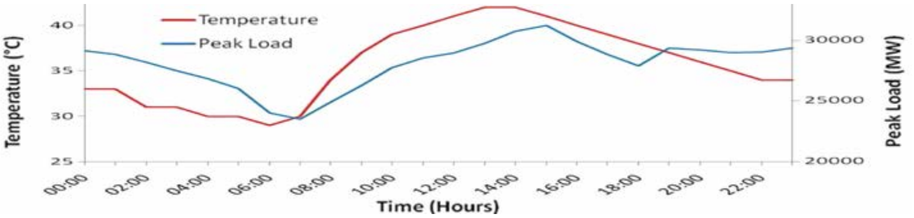


Fig. 1.3 Daily Variation in Peak Load with Temperature for Riyadh, Saudi Arabia 9 September 2006[25]

While high peak electrical loads are often part and parcel of life in a desert, nighttime temperatures in colder months regularly dip well below freezing. Temperature swings in both desert and temperate climates can often swing more than 56°C (100°F) between day and night, winter and summer. Such extremes clearly drive heating and cooling costs and beg for a new approach.

If a type of building covering could be developed that rejected substantially more solar energy in hot conditions while more effectively retaining building heat during cold conditions, than conventional approaches, then a substantial reduction in electrical load may be achieved.

Thankfully, such a family of building coverings has indeed been painstakingly developed over the past eight years. Conceived by R. P. Barrett, the basic driving premise of such thermally adaptive building coverings is to use shape-changing properties of adaptive materials to improve performance. Towards that end, new families of thermally adaptive shingles, siding, roofing and ventilation have been conceived, reduced to practice and tested in the lab and the field.

The basic enabling concept of Thermadapt™ thermally adaptive building coverings is that changes in ambient solar and thermal loading conditions leads to gross shape changes. Those gross shape changes occur not through a complicated electrical feedback network or control system, but the inherent properties of the laminated materials themselves. Such building coverings are designed and built to shade a building from solar radiation while minimizing heat transfer to the outer walls during high heat conditions. Conversely, during cold conditions, the same covering reverses shape, forms a nearly airtight pocket of dead air and more completely insulates the building.

While many adaptive materials can make this happen, because building coverings are very cost-sensitive, shape-memory alloys, polymers, gels, electrostatics, magnetorheological and other complicated actuation techniques can be easily shown to be cost-prohibitive. One reliable concept has been shown over the past three decades to minimize costs of actuator structures. By using coefficient of thermal expansion (CTE) mismatch, a new family of building coverings can achieve just the prescribed performance above for minimal cost with respect to other families of adaptive materials. If the principles of CTE mismatch lamination are properly employed, then this new family of thermally adaptive materials will curl up, shading a structure in high heat conditions and conversely curl down in cold conditions as shown in Fig. 1.4.

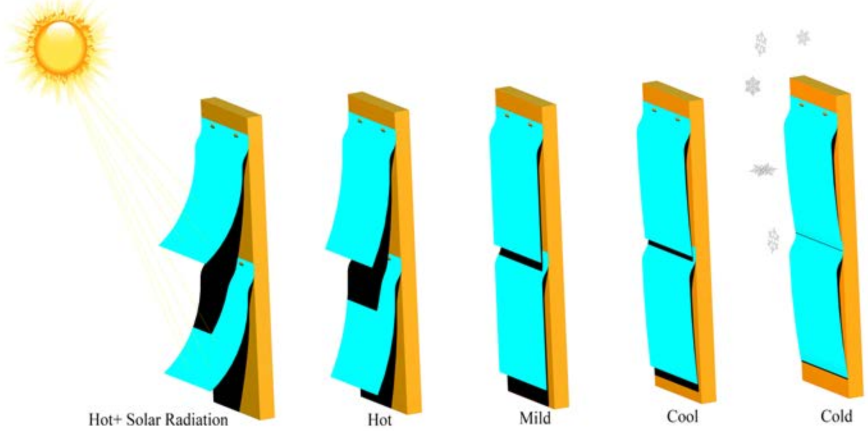


Fig. 1.4 Basic Thermo-kinematics of Thermadapt™ Thermally Adaptive Building Coverings

Clearly, to make lamina with characteristics as shown in Fig. 1.4, the structural material will have an outer layer which possesses a lower CTE than the inner layer. Accordingly, as the laminate heats up, the inner layer will tend to expand at a more rapid rate than the outer layer. This differential will cause the laminate to curl away from the structure in high heat conditions. There are many many permutations of this basic design including the addition of various ancillary layers of foam, interstitial layers, root stand-offs, damping treatments, amplification methods, anodization, surface coatings, paint and edge guards among many others. In spite of the numerous permutations, the basic concept remains the same: outer structural layer = low CTE, inner structural layer = high CTE.

2. Range Test Articles

Following successful tests of the subscale buildings, a trio of nearly identical full-scale buildings were fabricated and tested. These buildings were erected on the site of the Thermadapt™ test range in Holden, Missouri on a treeless rise more than 300m (1000ft) from the next closest structure and road in an East-West line. The buildings were fabricated in March 2012 from 12.7mm (0.5 inch) thick pressboard as shown in Figures 2.1 and 2.2. Figure 2.2 shows the test facilities being erected and temporarily braced.

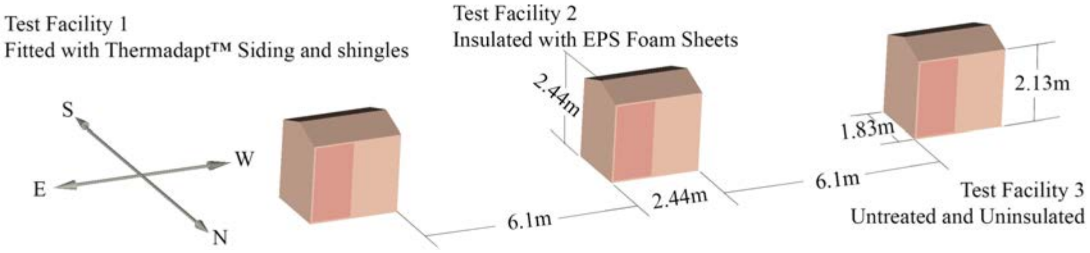


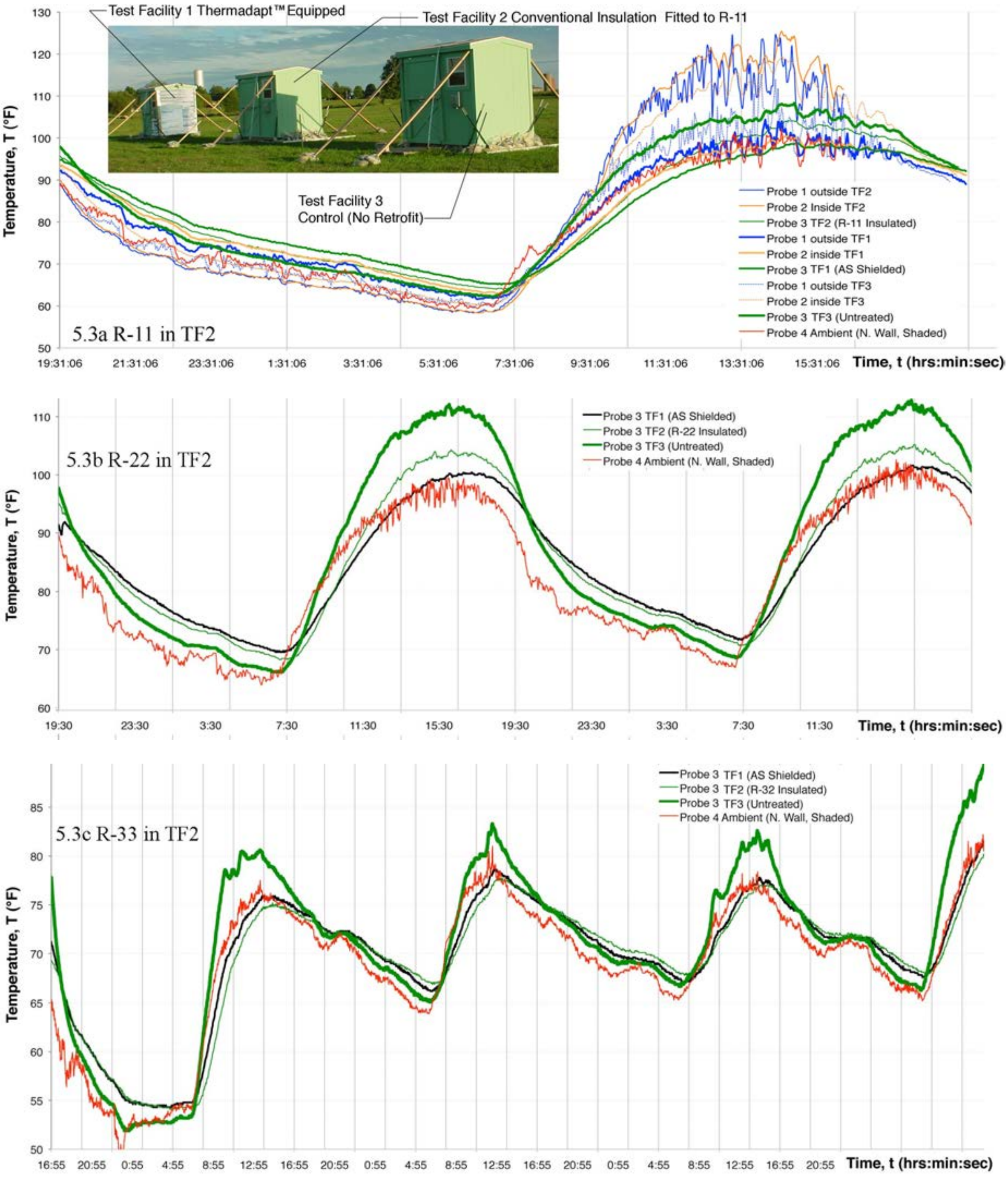
Fig. 2.1 Layout of the Full-Scale Thermadapt™ Outdoor Test Range with Test Facility Geometries

Fig. 2.2 Thermadapt™ Full Scale Test Facilities in the Fabrication Shop and on the Outdoor Test Range: Fabrication, Erection and Operation

The test facilities were outfitted with eight channels of data collection taken by a pair of Omega RDXL4SD dataloggers sampling at 30 samples/hr via K-type thermocouples. The site was wired for data collection off the grid and solar powered with the ability to run day and night around the year unimpeded. Testing began in May of 2012 and has continued through 2016. Test Facility 1 was fitted with Thermadapt™ adaptive siding and shingles. Test Facility 1 contained additional data logging capability due to the additional numbers of unknowns. Test Facility #2 was used to test the effect of different numbers of layers of EPS foam added between and on the inside of the inner walls and studs. The purpose of the multiple layers of EPS foam was to arrive at a level which would emulate the performance of the Thermadapt™ siding. Test Facility #3 was untreated and acted as a control. The data loggers in each of the three facilities were accessible on secure boxes which were mounted just below the only window shown on the left hand side of Figure 3.9. This was done so that the buildings would not have to be opened to exchange data cards which would have corrupted several data points with erroneous spikes. It should be noted that there was only one window and one door, both on the North side of each of the test facilities. The bottoms of the test facilities were completely floored with 12.7mm (0.5”) thick plywood flooring and seven studs running transversely across the underside of the flooring. For building stability, each test facility was ballasted with 120kg (265lb) of cement blocks on the building corners.

3. Range Test Results

Full-scale tests were initiated on the buildings shown in Fig. 2.1 and 2.2. Testing in the Summer of 2012 showed similar trends as the subscale structures, but a different test protocol was established so as to establish an “equivalent R-value” for the Thermadapt™ siding and shingles. Test Facility 1 (TF1) was retrofitted with Thermadapt™ building coverings on the East, South and West walls of the building and the roof. TF3 was left bare with the painted pressboard siding as fabricated. TF2 was calibrated as it was initially fitted with no insulation (matching TF3) and checked against the centroid temperatures recorded in TF3. Internal probes showed temperature matched late Spring and Summer temperatures within 0.3°C between the two buildings (without insulation). Then TF2 was retrofitted with Dow-Corning 8.9cm (3.5”) EcoTouch R-11 pink fiberglass insulation on all walls and ceiling. Fig. 3.1a shows the results of the R-11 tests (one layer of insulation). Then TF2 was retrofitted with R-22 levels of fiberglass insulation lining with results shown in Fig. 3.1b. Finally, TF2 was retrofitted with three layers (R-33) of fiberglass insulation as shown in Fig. 3.1c. Figures 3.1 a, b, and c show successively the details of a complete day, then two days, then just over three days worth of data taken at 120s between samples for all three test facilities.



Figs. 3.1 a Data for One Complete Daily Cycle with TF2 Fitted with R-11 Fiberglass Insulation, 3.1b TF2 Fitted with R-22 Fiberglass Insulation, 3.1c TF3 Fitted with R33 Fiberglass Insulation, August – October 2012

Figures 3.1a, b, and c show consistent trends. Foremost among them is that the centroid air temperatures in the Thermadapt™ fitted test facilities (black lines) exhibit daily temperature peaks that are typically at or below ambient temperature peaks (red lines). Similarly, the nightly lows of the Thermadapt™ fitted test facilities show higher lows than ambient, which, of course, is indicative of the insulation effects by Thermadapt™ element closure. Conversely, the untreated TF3 shows centroid air temperature peaks which are 6 – 8°C (10 – 14°F) higher than the Thermadapt™ fitted test facilities. It is also shown that the Thermadapt™ building coverings work as well as R-33 levels of insulation. Of course, the amount of insulation added to TF2 which was required to match the performance of the Thermadapt™ fitted test facilities was so great that TF2 lost roughly 1/2 of its internal volume which simply was occupied by 27cm (10.5 in) of fiberglass on all of the sidewalls and ceiling. Given that the Thermadapt™ building coverings which were used measured 8mm in total external standoff thickness, this gives them an "equivalent" R-value of roughly 40/cm (100/in).

The reader is asked to note once again that an extremely large bulk of data was gathered through a full calendar year, which is far too voluminous to present in this medium. However, the trends were consistent between the seasons that the "equivalent" R-values were within 20% of the values above for all seasons.

4. Conclusions

i. Thermally adaptive siding and roofing can be used as highly effective building coverings;
ii. When mounted on full-scale structures, thermally adaptive lamina modify the thermal transfer properties of the building so that its response to thermal loading of the treated building resembles a structure which has been fitted with layers of insulation which are built up to R33.

5. Coming Work on Thermally Adaptive Lamina and Work to be Published

The work presented herein is a highly abbreviated version of a much more complete paper. Accordingly, the reader should understand that accurate theory has been established which correlates well with experiment, coupon, test chamber and subscale building studies have been done with outstanding results at every level.

Because the work reported here is three to seven years old, it should be obvious that a nontrivial backlog of other investigations on thermally adaptive lamina have been conducted but have yet to be published. In the intervening time since this work on thermally adaptive lamina was first commissioned, the intellectual property associated with this line of technology was methodically protected via US and international patent filings. Coming publications on thermally adaptive lamina will include data on responses to wind loads, hail and fire. Also many more advanced techniques enhancing fatigue resistance, acoustic properties, safety, deflection levels and form factors with temperature have been studied and will be published. Several other applications of this general line of technology have also been explored and will be reported. Of great importance is fabrication of the preferred lamina configurations for building coverings and other applications. Accordingly, economics studies involving cost of materials and optimization of fabrication techniques to minimize costs have been conducted and will be published. The goal was to generate fabrication methods that suppress costs so that both acquisition and installation costs would be on a par with conventional siding and roofing materials.

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