

# NEW MATERIALS AND CONCEPTS TO REDUCE ENERGY LOSSES THROUGH STRUCTURAL THERMAL BRIDGES

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## ABSTRACT

Building envelope thermal anomalies (BETAs) particularly thermal bridges in structural members are a significant source of energy loss in buildings. An assessment of the various types of major structural thermal bridges and their impact on energy conservation, building degradation, occupational health, and personal comfort has been undertaken. As part of the study, an evaluation of new concepts and the potential of utilizing new materials as means to eliminate or minimize the effects of thermal bridges was included.

Developmental materials, as well as improved designs and modifications of existing materials, are described. New materials, especially fiber reinforced composites and honeycomb composite systems candidates for lowering heat transmission characteristics in structural members, are identified and discussed with respect to transfer of new technology to the building industry; cost impact on overall design, construction and operation; and potential for innovative practices.

Recommendations are made for the appropriate building design and construction sectors to develop new structures containing fewer BETAs.

## INTRODUCTION

Building envelope thermal anomaly (BETA) can be defined as a material or configuration in a building which produces localized excessive heat flow from (or to) the building and a cold (or hot) area on an interior surface of the building.

Excessive heat flow is heat flow beyond that normally modeled by traditional building energy analysis methods. Traditional methods assume spatial and temporal uniformity of elements and include one-dimensional conductance loss through wall segments, conductance through window glass, isothermal zone infiltration losses, forced ventilation losses, and radiation losses through glass area. A BETA does not include phenomena caused by moisture accumulation.

A thermal bridge is a BETA caused solely by heat conduction processes. BETAs are composed of and/or affected by the following.

### Structural Elements

In one sense, any element of the building is a structural element if it is contained in the structure. However, a structural element is intended to mean those members of the

building that carry primary loads, any may therefore resist thermal "breaking" because of the need for rigidity and strength to perform the primary function. Structural elements would include girders, studs, joints, plates, foundations, purlins, I beams, etc.

The significance of structural elements is that they are normally composed of high strength materials that usually have comparatively high thermal conductivity properties. These materials must connect with the next element of the building structure, ultimately leading to a point near, or connected to, the outside building envelope.

#### Component Connections

Component connections are arrangements necessary to hold components in place within the framework of the building envelope. Window casements, door frames, and the hardware for fastening these into place are examples of component connections. The methods of connections are not always identical in every structure. For example, connections in a metal/masonry industrial-type building or high rise structure will differ in arrangement to those in an ordinary "stick-built" house. Any facet of these connections (e.g., fastening of the casement to the structure or fastening the casement to the glazing) that provides a heat path may be regarded as a thermal bridge.

#### Envelope Penetrations

Envelope penetrations consist of any metallic or other heat-conducting materials that must necessarily penetrate the building envelope, carrying heat in or out circumventing normal insulation arrangements. Examples include closet stacks that penetrate the roof, chimneys, hood vent ducting, utility conduits, or pipes such as those used for filling oil tanks.

#### Corner Effects

"Corner effect" is a term used to describe the flow of heat in any direction that provides a preferential conductive path. At corners, the geometry provides two-dimensional conductive paths that allow more heat flow than simple one-dimensional paths through the planar walls that form the corner. Heat flows laterally along a wall to reach a broader area for heat loss; similarly, it might flow through a concrete foundation in order to dissipate into the earth along the earth contact area. Heat flows along a readily conducting path in order to dissipate through the sides of the path over a broader area which itself may have a lower heat transfer characteristic. Commonly called the "fin effect," this process uses the principle employed in finned tubing heat exchange. In a sense, the term "geometrical effect" is more apt.

#### Faulty Workmanship

Faulty workmanship consists mostly of improper installation or omission of insulating material which was otherwise properly designed and specified.

Thermal bridges are known or suspected to be sources of significant energy loss in buildings. They can contribute to serious moisture problems affecting personal comfort and occupant health, as well as causing rapid building degradation necessitating costly repair and rehabilitation. Eliminating or minimizing the effects of thermal bridges, especially by utilization of new materials or concepts, could be one way of making significant energy savings and reducing maintenance and replacement costs.

With the growing realization that thermal bridges can cause energy loss and building failure, Oak Ridge National Laboratory and the U.S. Department of Energy commissioned Dynatech R/D Company to undertake an assessment of structural thermal breaks in buildings. The primary goal of the study was to collect and assess information on the types, forms, and effects of the most common thermal bridges, excluding fenestration, and the availability of new materials and/or concepts that are available to create thermal breaks.

As part of the study, researchers participated in (1) a literary search of over four hundred listings; (2) interviews and discussions with over 150 members of industry, government, and academia involved internationally in the design, construction, and operation of, and materials development and manufacture for, buildings; and (3) the organization of a two day workshop on the subject.

This paper addresses specifically the area where new and modified materials and/or concepts have been or can be applied.

## RESULTS OF LITERARY SURVEY

A literary search was conducted to provide part of the background information necessary to assess the state-of-the-art materials used to mitigate the effects of thermal bridges in structural components in buildings. Over 400 abstracted citations were printed and reviewed, of which only about 10% were deemed to be pertinent.

By far the most common categories among the papers reviewed were the detection of BETAs and assessment studies. The emphasis within the first category was in thermography and energy audit techniques. References dealing with methods for mitigating thermal bridges were found primarily in manufacturers' literature and in the abstracted patents. Many of the papers dealing extensively with thermal breaks were either from European sources, particularly France, Belgium and Sweden, or from governmental agencies within the United States and Canada.

The citations were categorized as follows.

### BETA Detection

- Thermography
- Energy audits
- Heat flux transducers; other in-situ measurements
- Condensation

The results of various analytical, field, and laboratory studies indicate that in large buildings heat loss due to thermal bridges can be at least 20% greater than expected (Fang et al. 1984; Granum 1980; Grot et al. 1983; Spooner 1982).

### Assessment Studies

- Analytical determination of the magnitude of heat loss problems from BETAs
- Resolution of differences between predicted and measured heat loss from buildings

Basically the results of these types of studies (Berthier 1973; Brown and Wilson 1963; CSTB 1977 a & b; Johannesson 1981; Nevander 1961), especially those undertaken by Centre Scientifique et Technique du Batiment (CSTB) in France, indicate that the current methods of analysis are less than satisfactory. Specific guidelines and practical rules were provided in order to evaluate the importance of a particular type of thermal bridge and how its effects could be reduced.

### Mitigation Techniques

- New materials for fastening insulation systems
- New materials to replace high thermal conductivity structural components
- Insulation application techniques
- New construction techniques

Several papers in this group were relevant to the present discussion. Three concepts in particular are worth noting. First, Machaj and Zakrzewski (1980) discussed the merits of steel structures versus concrete in terms of building heat losses. They recommended four

techniques to reduce heat loss in steel buildings: (1) reduce the thermal bridge cross section; (2) increase the heat flow path length; (3) use highly insulating materials in series with the thermal bridge; and (4) reduce the "fin" effect.

Metal studs with longitudinal slots forming thermal breaks were analyzed, and a number of built-in wall sections were tested to determine the benefit of using such studs to minimize heat losses. The analysis and test showed that the thermal resistance of an insulated metal stud wall using slotted steel studs was 25 to 30% higher than that with solid steel studs.

The Roki double wall, new wood frame dwelling construction technique which substantially reduced the degree of thermal bridging, is now available (Energy Design Update 1984). This wall has no top plates or sole plates to hold the inner and outer walls together. Instead the walls are tied together by 16-gauge steel tie plates attached 4 feet on centers between floors. Insulation may be blown into the wall cavity from the attic to form an unbroken envelope of insulation from the foundation sill plate to the attic (with the exception of the relatively narrow steel tie plates).

A new urethane foam building block (Case 1984) has recently become available. The block is the same general shape as a conventional concrete block. However, it weighs less than 0.5 kg, rather than the usual 14 kg. The blocks, called Insul-Blocks, would normally be used in conjunction with recommended concrete rebar reinforcement to yield a wall claimed to be as strong as a conventional block wall. The R-value of such a wall is claimed to be substantially higher than that attained with conventional foam-filled concrete blocks or normal insulated stud walls. Insul-blocks cost approximately 25% more than concrete blocks. However, the construction labor costs are reported to be relatively low.

## NEW MATERIALS SOLUTIONS TO THERMAL BRIDGING

### General Considerations

The object of any thermal break is to minimize direct heat conduction along or through a particular structural component. This can best be accomplished by (1) directly reducing the thermal conductivity,  $\lambda$ ; (2) increasing the thermal resistance at contacting surfaces by introducing low conductance fillers and stand-offs; and (3) reducing the cross-sectional area of the conducting source.

It is unlikely that large reductions can be made in direct conduction effects by reducing either  $\lambda$  or the area of most conventional materials. For example, replacing structural steel ( $\lambda \approx 40\text{--}50 \text{ W/m}\cdot\text{K}$ ,  $280\text{--}350 \text{ Btu}\cdot\text{in/h}\cdot\text{ft}^2\cdot\text{F}$ ) with stainless steel ( $\lambda \approx 12\text{--}15 \text{ W/m}\cdot\text{K}$ ,  $80\text{--}105 \text{ Btu}\cdot\text{in/h}\cdot\text{ft}^2\cdot\text{F}$ ) would provide only small positive effects since  $\lambda$  is comparable. In Europe, stainless steel ties have been used between two masonry courses to produce resistance to corrosion and to increase durability. The thermal effect though small, was an unexpected bonus. Advantages arise due to the improved strength of the stainless steel, allowing for some size reductions in the size of the ties, but these advantages are offset considerably by the large increase in initial cost.

To attain highly significant effects,  $\lambda$  has to be reduced by at least an order of magnitude. In addition, the materials, even those used at joints, must retain the structural properties of those currently in use. This combination of factors leads automatically to consideration of the new range of lightweight, reinforced composite materials and systems with  $\lambda \approx 0.2\text{--}2 \text{ W/m}\cdot\text{K}$  ( $1.4$  to  $14 \text{ Btu}\cdot\text{in/h}\cdot\text{ft}^2\cdot\text{F}$ ). Though these materials have not been developed primarily for buildings (Standardization News 1983), the state-of-the-art is such that many of them are or can be made available in the size and forms required for use in buildings (Banes 1981; Holmes and Just 1983).

The major deterrent is that of initial materials costs. However, the new materials give rise to a number of changes that offset those costs. Those changes include the possibility of utilizing smaller HVAC and ancillary equipment, and reduction of both transportation and construction costs. When these money-saving changes are combined with the general advantages of introducing thermal breaks e.g., energy conservation, improved durability, reduced maintenance, the possibility of using new materials to minimize the effects of

thermal bridging becomes more viable. The application of old and new materials technologies should produce significant changes in future design and construction.

As part of the study, over 150 members of industry, government, and academia were interviewed. They are categorized in five groups, including (1) architects, designers, and engineers, (2) builders, construction organizations and unions, (3) organizations associated with conventional construction materials, (4) organizations associated with new materials, and (5) government and research organizations. Efforts were heightened to interview members of the latter two categories since information related to new materials was more likely to be available from those involved in development and research. The general responses from all categories are summarized as follows.

Architects, Designers and Engineers. This community, as a whole, was cognizant of the structural thermal bridge problem and of its impact, especially in a qualitative sense. Interviewees claimed that every effort was made to reduce the number and type of anomalies in the design of the buildings being studied. Furthermore, where bridges occurred, appropriate means to minimize their effects were described and detailed on the plans. However, interviewees further claimed that instructions were often either not followed correctly or ignored during the course of construction. In certain buildings, designed for a particular use or sponsor, the aesthetics often clashed with engineering and operational considerations. Increased economics was the major factor cited as the overall deterrent to the utilization of new materials and newer, possibly more complex, designs.

Builders, Construction Organizations and Unions. In general, the small builder is becoming aware of energy conservation issues, especially the need for thermal insulation and energy efficient doors, windows, and equipment. However, apart from a significant minority involved in developing the "superinsulated" houses, the tendency is for builders to follow conventional conservation practices at the lowest cost. There is little encouragement to introduce changes due to initial increase in cost and, in some cases, excessive structural requirements to meet the needs of the current building codes.

External insulation sheathing is being used more often to reduce the direct effect of the thermal bridge on the outside environment. However, there are still many areas, such as multistud corners and masonry-metal stud constructions, where significant reductions in thermal bridging could be made with new lightweight, high-strength, low-thermal-conductivity materials.

Although the architect has taken steps to reduce or eliminate thermal bridges, the means to do so may be impractical for the contractor. Because different stages of construction are handled by different tradesmen, vital materials and components may be omitted, or those already installed may be damaged. Repairs and retrofit measures are expensive, and again may involve different trades-people and subsequent conflicts.

Overall, neither builders nor contractors are aware of any major materials developments. Furthermore, they have little appreciation of the total impact of thermal bridging effects. As a group they intend to continue using conventional building practices until less expensive means are forthcoming.

Organizations Associated with Conventional Construction Materials. Because of escalating costs, there has been no concentrated effort to develop materials solely for the reduction of BETAs and their effects. Most work has been directed toward the improvement of existing materials or the modification of materials for individual applications. For example, existing materials may be replaced with those having a lower thermal conductivity (e.g., metal piping replaced with plastic), or a design may be modified by utilizing a design concept that calls for less material.

Organizations Associated with New Materials. This particular group would appear to have the most potential for introducing new materials into the building and construction industries. However, it is generally unaware of, and consequently has not addressed, the thermal bridge issue.

Materials are usually developed for nonbuilding applications. In many cases, especially with the continuous fiber reinforced plastic and other matrices, the mechanical, thermal, and other properties can be tailored to meet specific design requirements. For many applications, particularly for space and military needs, advanced development has been

undertaken without the fiscal constraints associated with commercial enterprise. The same technology could be channeled to the building regime as is currently being utilized in a variety of related areas: refrigerated transport vehicles; recreational vehicles; curtain wall components; structural shapes, sidings, and internal furnishings; bridges and other high load components; ship superstructures and marine structures; and corrosion-resistant structures and processing equipment.

Clearly these materials and components must be considered as having potential in building applications. There is a definite need for increased technology transfer to the building community, combined with the need for this materials group to be made more aware of the needs of the building community.

Government and Research Organizations. Most material-related work is being carried out for and by agencies of the Department of Defense. One particular area of development involves completely metal-free structures that have very high structural stability and stringent temperature control to house computers and electronic equipment in an interference-free environment. A second area of development concerns relatively large, easily transportable and/or assembled shelters and buildings having high structural stability and integrity. These buildings are needed both to house people and provide particular service functions such as hospitals and communications centers in very cold and hot climates. The large-scale use of composite components in such buildings is a viable concept. Though these efforts were not commissioned with thermal breaks in mind, the fact that the use of such materials and design concepts can reduce thermal bridging effects is an added bonus.

### Specific Materials

#### Thermal Insulation

In many designs the impact of a structural thermal bridge is foreseen and attempts are made by the architect to reduce the effects by calling for the introduction of thermal insulation in and around the bridge. However, installation of thermal insulation can be difficult or impractical, and quite often such insulation is omitted, not installed correctly, or even removed or ruined after installation.

More recently, several thermal insulations have been introduced, one claim of which is that they address the thermal bridge issue. These materials include the following.

- Some spray-applied fibrous glass and cellulose fiber insulations having a thermal conductivity of  $0.036 \text{ W/m}\cdot\text{K}$  ( $0.25 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot\text{F}$ ) are designed for pneumatic wet spray application using fire resistant adhesives. These materials are said to be very good for applications in small, hard-to-access areas. In addition, when suitably surface treated they can be used for total insulation of building envelope surfaces, including external surfaces, especially of metal buildings.
- Modified polyisocyanurate, polyurea and polycarbonilide foamed plastics are also used for similar applications to the above. Such materials can be sprayed, injected, poured or frothed in place in small areas and in wall cavities. They are said not to have the high gas pressure effect of formation which was the problem associated with earlier polyurethanes. When suitably protected from the environment, they are used for exterior insulation, thus providing an overall blanket thermal break effect to the internal structure.

Two promising materials are now available as board stock to supplement the existing cellular plastics. These are the closed-cell fluorocarbon-blown phenolic and polyvinylchloride (PVC) materials. Both materials may be considered as highly improved versions of previous open-cell or partially closed cell products. Both have improved fire resistance characteristics over many of the existing cellular plastic insulations and are being utilized in more applications, particularly on the exterior of the building envelope.

The fluorocarbon-blown phenolic foam materials were developed initially as insulation boards for roofing applications. Higher-strength versions are now becoming available for external sheathing boards. The major point of interest with the closed-cell phenolic foam is a very low initial thermal conductivity of approximately  $0.016 \text{ W/m}\cdot\text{K}$  ( $0.11 \text{ Btu}\cdot\text{in}/\text{h}\cdot$

ft<sup>2</sup>·F) coupled with very slow aging characteristics. Unlike other fluorocarbon blown foams (which age relatively quickly unless protected by thick impervious skins), the phenolic foams appear to be much more resistant to exchange of gas within the pores. It is believed that this is due to a combination of smaller cell size, thicker, less permeable cell walls, and a lower solubility of the fluorocarbon in the polymer. However, overall long-term aging, dimensional stability and other characteristics are not yet known due to the fact that the material has been available for only about four years.

### Insulation Panels

Currently there is an array of sandwich insulation panels having a high thermal resistance equivalent to or greater than that for a conventional wall. These usually consist of a core of insulation such as a cellular plastic or fibrous glass product contained between thin rigid skins, which can consist of a high density reinforced plastic, masonry or metal (Long and Weinhardt, 1982). Such panels have been used particularly for refrigerated cargo vehicles, recreational vehicles and mobile homes. More recently, designers have been using them for the building envelope, especially for curtain wall constructions. Thus, both designers and fabricators are taking steps to ensure that the panel constructions and their methods of attachment are such that thermal breaks are introduced wherever feasible. In addition, the thermal bridges at the panel joints are being addressed by various means including tongue and groove, adhesive-bonded and staggered overlap joints. These ensure that the joints consist of low conductivity materials or contain high resistance layers as the breaks. Newer panel consisting of graded-density fibrous glass insulation with high-density fiber-reinforced plastic or paper skins have also been developed to have good thermal and structural performance.

The methods of attachment operate with standoffs of low conductivity materials so that there is no direct contact between the higher conductivity frame and skins, especially if the latter are metal. Blind fiber reinforced epoxy and other polymer rod and bolts are utilized for attachment to replace metal nails or screws, ensuring that there is no complete or direct thermal bridge from the panel exterior to the internal structure. Adhesive bonding is now widely used for attaching panels to framing members and for joining the panels to each other. The normal method for joining masonry-faced panels is to ensure that a small gap exists on the outside between mating concrete faces. This is filled subsequently with insulation plus a protective coating.

### Masonry

The need to develop masonry building components with lower thermal transmission coefficients has taken two major courses. The first is the development of block concepts which reduce the area and length of the web and provide easy means to introduce thermal insulation inserts. The second has been directed towards reducing the thermal conductivity of the basic concrete of the block. In each case, the structural properties and integrity of both the concrete and the block have to be maintained to conform to design requirements.

In general, most existing masonry structural lightweight concretes have densities in the range of 1400 to 2100 kg/m<sup>3</sup> (90 to 130 lb/ft<sup>3</sup>), thermal conductivities in the range of 0.7 to 1.4 W/m·K (5 to 10 Btu·in/h·ft<sup>2</sup>·F), and compressive strength of approximately 17 to 60 MPa (2500 to 9000 lb/in<sup>2</sup>). Currently, research in the USA, Canada and United Kingdom is oriented towards producing lower-density concretes of approximately 1050 kg/m<sup>3</sup> (65 lb/ft<sup>2</sup>) with adequate compressive strength of approximately 10 to 13.8 MPa (1500 to 2000 lb/in<sup>2</sup>) having correspondingly lower thermal conductivities of less than 0.4 W/m·K (2.8 Btu·in/h·ft<sup>2</sup>·F). In order to accomplish this, various aggregate materials, including graded livite and gravelite, polystyrene beads and perlite, are being studied. Strengths in the acceptable range have been produced together with reduced thermal conductivities of approximately 0.19 to 0.43 W/m·K (2 to 3 Btu·in/h·ft<sup>2</sup>·F). An alternative concept is to use glass fibers as reinforcement of the concrete.

### Bonding Materials

One of the major contributors to increasing thermal bridging effects, particularly in masonry structures, is the contribution of the mortar in the joints. Conventional mortars have a high density of approximately 2100 kg/m<sup>3</sup> (130 lb/ft<sup>3</sup>) and a thermal conductivity in

excess of  $1.7 \text{ W/m}\cdot\text{K}$  ( $12 \text{ Btu}\cdot\text{in/h}\cdot\text{ft}^2\cdot\text{F}$ ). This form of thermal bridge is being addressed in two ways. In the first the masonry blocks are stacked dry and surface bonded with a glass fiber-reinforced plastic cement bonding material. This method eliminates the thermal bridge of the mortar, but introduces a continuous thin shell of relatively high thermal conductivity of  $1 \text{ W/m}\cdot\text{K}$  ( $7 \text{ Btu}\cdot\text{in/h}\cdot\text{ft}^2\cdot\text{F}$ ) bonding material as an additional thermal bridge. The effects of this can be reduced further with a thermal insulation material or system overlap. The other means of addressing the thermal bridge problem has been the development of lower thermal conductivity epoxy or plastic mortars and grouts which are applied in the normal manner.

### Wood

Pressure Treated Wood. These materials, especially with newer fire and other retardants to reduce fire potential and effects of fungus and insects, are now becoming more highly utilized in frame and light commercial constructions. In particular, there is a return to the all-wood foundation in combination with an adequate external water retarder rather than the now more generally used concrete. The replacement of dense concrete having a thermal conductivity of 2 to  $3 \text{ W/m}\cdot\text{K}$  ( $14$  to  $21 \text{ Btu}\cdot\text{in/h}\cdot\text{ft}^2\cdot\text{F}$ ) with wood having a thermal conductivity of approximately  $0.15$  to  $0.2 \text{ W/m}\cdot\text{K}$  ( $1$  to  $1.4 \text{ Btu}\cdot\text{in/h}\cdot\text{ft}^2\cdot\text{F}$ ) produces immediate significant reductions in thermal bridging effects, especially to the ground. A further claimed advantage is that the hollow wall cavities of such foundations are more easily insulated.

-- Structural glue laminated timber refers to engineered stress-rated products consisting of assemblies of selected and prefaced laminations securely bonded together with adhesives. These products are being used widely as structural members for floors and roofs, particularly in smaller service and recreational buildings. Such structural members are available for special curvatures as well as special roof designs. The grain of the laminations is parallel to the length, and individual laminations are thin, not exceeding 2 inches in width. In all cases this lower thermal conductivity wood product replaces higher conductivity structural members. Where used instead of ordinary lumber there is a reduction in the amount of and the cross section of the laminated product needed to offset the 20 to 30% increase in conductivity.

### Fasteners

The development of metal windows and particularly of multiple glazed units produced a corresponding need for introducing thermal breaks. This is one of the few areas where materials development addressed the issue directly.

Metal windows and multiple glazed units have been available for some years and are now being used, as mentioned earlier, both as low conductivity standoffs at joints and as lateral tie rods in masonry and insulated concrete construction. One such composite panel wall consists of an array of such tie rods fixed in the insulation panels and extending on both sides. Concrete is poured on either side of the panel and allowed to set. This forms a rigid composite panel with the tie rods holding everything together but not extending all the way through each concrete layer. In all cases where such plastic tie rods and standoffs are utilized, if additional mechanical strengths are required, fiber reinforced materials can be used.

### Potential Materials and Systems

Basically there are two general types of materials -- fiber and other reinforced plastics -- as well as honeycomb systems which may also contain the reinforced plastics.

-- Reinforced Composites. These materials have been growing in use for many and varied applications for some four decades. Their first major use as structural components was in aircraft during World War II. Many advances both in materials and fabrications techniques have occurred since that time, and the technology is such that the "all composite aircraft" is now flying.

Materials such as glass or aramid reinforced plastics have three to six times the strength-to-density ratios of common steel and aluminum with equivalent stiffness-to-density

ratios (Young's Modulus). Continued improvements in fiber type, form, and in the matrix materials allow further improvements in properties to be foreseen. Composites are now fabricated by many different and convenient processes and are used for a wide variety of applications ranging from space structures to tennis racquets. They are potential candidates anywhere lightweight, strong, stiff and durable materials are required.

The additional advantage in the thermal break context is the fact that they have lower thermal conductivities than structural metals. The thermal conductivity varies with the type and amount of reinforcement and with the fiber direction, but for the reinforced plastics it ranges from 0.3 to 3.0 W/m·K (2 to 20 Btu·in/h·ft<sup>2</sup>·F). This is considerably below conventional structural steels and aluminums, which range from 40 to 210 W/m·K (300 to 1500 Btu·in/h·ft<sup>2</sup>·F). As a replacement for wood construction structural members, reinforced plastic is of higher thermal conductivity, but is of considerably less mass and bulk. It is also conceivable to foresee the replacement of a thick I-beam by thinner metal channel sections joined by composite sections.

Another significant potential advantage is the flexibility of choice and the opportunity for creativity that these materials allow, especially in design and in fabrication of large prefabricated units. By appropriate choice of reinforcement materials the properties can be "tailored" to meet specific structural or thermophysical properties requirements. Thus, it is possible to provide greater strengths and stiffnesses in specific areas (e.g., around attachment holes and the arrangement of reinforcements such that desired shapes, including curves, can be formed during manufacture to provide very stable materials that exhibit zero or very low thermal expansion).

It is only recently that composites have started to be utilized in buildings. Their use has been more for specialized needs alone and not with any idea of addressing the BETA issue. The very recent developments of more fire-resistant resins for the matrix now make these materials even better candidates for building applications.

Two major manufacturers have shown that a very wide variety of structural shapes, beams, tubes and sheets in a large number of sizes can be fabricated readily by pultrusion techniques. The first of these manufacturers has fabricated truss beams some 12m (40') long and 0.8m (2'6") deep consisting of 14 panels with all two-bolt connections. This beam will support 8700 N/m (600 lb/ft) with a safety factor of 2:1. The ultimate tensile and compressive strengths are each 14 MPa (20,000 lb/in<sup>2</sup>). Beams up to 18m (60') can also be fabricated in a similar manner.

The second manufacturer has fabricated both simple and more complex building structures of up to three stories with some of these materials. Such buildings have been necessary to house computers and electronic equipment shielded from all types of electrical interference. The buildings themselves consist of a carefully designed framework of solid and hollow beams, supports, tubes and rods joined together with bolts, rods and studs of the same materials. Conventional insulating, together with nonmetallic interior wall and ceiling units, is then added. The external finish consists of fiber-reinforced plastic sheets.

Currently, the cost of such materials is somewhat higher than conventional metal and wood; the basic extruded materials are some four to five times the cost of structural steel. However, they are 100 times lighter than steel, albeit weaker. The current order of cost for delivery and installation of a three-story structure approximately 14m x 18m (44' x 55') is \$110 to \$150/ft<sup>2</sup>. This compares to \$15 to \$20/ft<sup>2</sup> for a conventional metal building. Current indications are that the costs can be reduced with volume and that the advantages in easier handling and construction techniques will offset some of this cost differential so that overall construction costs may become more comparable.

#### Honeycomb and Hybrid Composites

There are other types of composite materials or systems which were developed originally for aircraft applications, but which can be and have been used in buildings. Where used currently for building structures the prime purpose has not been to address thermal breaks. They have been utilized mainly for their lighter weight and structural integrity, and thermal breaks have been a bonus, due to the materials and to the designs using such materials.

Basically a honeycomb panel consists of an open or sometimes insulation-filled honeycomb adhesively bonded between facings. The core, while supporting the facings, provides stiffness and resists shear loads. The two facings take the tensile and compressive loads while the adhesive joint provides the torional rigidity to the whole panel.

The materials of the honeycomb and of the facings can vary, as can the cell size of the honeycomb and the thickness of the facings. The cores are fabricated from a variety of materials ranging from metals, fiber-reinforced plastics, plastics and paper. Facings can be of similar materials which for building applications are supplemented with such constructional materials as wall board, masonry, marble, wood, etc. The honeycomb core can be filled totally or partially with insulation, e.g., cellular plastic, while the two facings can be different. New fire-resistant resins and adhesives are available, both for the plastic matrix materials and the adhesives. Once again, great flexibility of approach is attained, and by a suitable choice of materials a panel can be designed to meet specific requirements.

Because of these factors such systems are more suitable for providing thermal breaks in structural members. The core itself can be fabricated from low thermal conductivity materials as can one or both facings, while the adhesive joint can introduce added thermal resistance. If necessary the influence of the core can be reduced further by the addition of thermal insulation, while fasteners and other attachments can be bonded adhesively or carefully designed into the panel to reduce further the effects of direct conductive paths. They have been used in this way for refrigerated trucks and transportable containers.

Honeycomb panels, including those containing insulation in the core, have been used in buildings only to a limited extent. They have been reserved mainly for internal partition walls and for some special curtain wall designs which have taken advantage of their flexible design. In one instance, for example, the honeycomb was used in a lightweight wall panel with an outer facing of marble. By using the honeycomb core first bonded to the marble it was found that a very thin sheet of marble could be cut, thus reducing the total cost of expensive marble while reducing considerably the weight and the thermal bridge effects.

The most relevant use of honeycomb panels in building structures has been the recent development by several manufacturers of lightweight, structurally stable, blast-resistant, temperature-controlled, easily transported and handled shelters and buildings for the Department of Defense. These prefabricated living and service buildings were designed to operate in various climates ranging from the arctic to tropical environments and had to address the thermal bridge issue.

#### CONCLUSIONS AND RECOMMENDATIONS

BETAs are abundant in current buildings and some are probably highly significant although their total impact is not yet realized. There is now an awareness that thermal bridges are sources of energy loss and a major contributor towards building degradation. So far there has been no systematic effort to assess and catalog the overall significance of the different types of thermal anomaly.

The solution to summarizing the effects of thermal bridges by the introduction of thermal breaks is now receiving some attention. However, the current efforts are sporadic, scattered and disorganized. The problem has been addressed in the following three areas.

- Companies manufacturing accessories, such as metal window frames and window and door casings have introduced breaks into their product. In addition, a small number of subsystems or connectors has been introduced with the specific intention of reducing heat loss.
- Metal building and refrigerated vehicle manufacturing companies have introduced thermal break technique into their systems due to the awareness of the importance heat loss problems in their metal structures.
- Some or modified versions of materials that reduce the thermal conductivity and overall thermal conductance, or increase contact thermal resistances are beginning to be utilized in some areas.

New materials and systems have been developed for other applications and their introduction into structures should be viewed as a challenge to the building community. Some of the more significant characteristics of the new materials and systems are summarized as follows.

- Fiber-reinforced composites, hybrid composites and honeycomb materials and systems having significantly improved thermal properties, while retaining adequate structural properties, are now available.
- Materials can be designed and fabricated to have specific properties for a given application and thus allow increased flexibility of choice.
- Whole structures up to three stories have been built completely with these materials for special purposes not related directly to the solution to BETAs.
- The design, construction, and regulatory code communities are not yet aware of the availability and application of these materials, nor of their potential impact.
- Initial material cost is significantly higher than that of conventional materials.
- Reductions in overall costs can be foreseen due to structural design improvements, increased usage, improved fabrication technique, lower transportation and construction costs, lower maintenance cost, and longer building lifetime.
- These materials have the potential to influence significantly both building design and practices.

Significant gaps exist both in the impact of BETAs and the means to reduce their effects. A concerted and coordinated effort by the various groups within the building community is needed in order to help resolve the current problems. This is a multifaceted issue which requires considerable work by the many groups in materials development and manufacture, the design and construction industries, government and regulatory bodies and academia. In particular, the effort should include

- collection and dissemination of information from all sources on BETAs and the factors affecting their impact;
- education of relevant groups to a higher level of knowledge about BETAs;
- encouragement of materials developers, particularly in nonbuilding applications, to address specifically the use of new materials as thermal breaks;
- integration and coordination of existing national and international technical research studies on economics, materials factors, and performance evaluation of both general and specific BETAs;
- creation and maintenance of a complete catalog format for BETA information. (This should contain identification, descriptive information, suggested modification and additions for inclusion in Architectural Graphical Standards plus any information on modeling, qualitative evaluation of any effects and any first or life-cycle cost data.); and
- encouragement of building codes organizations to examine their current documents to ensure that structural requirements are not overly conservative and that new materials and concepts are not excluded.

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