



MODELLING THE HEAT TRANSFER CHARACTERISTICS OF ARCHITECTURAL HONEYCOMB COMPOSITE PANELS

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Abstract: In modern architecture, manufacturers are trying to make improvements to the thermal and illumine properties of partition panels whilst enhancing durability, aesthetics and reducing costs. One innovative proposal is the use of honeycomb composite panels. The architectural manufacturers are however limited in the materials they can use, since having an aesthetically pleasing product is as significant as providing a good insulation. This paper investigates the use of honeycomb composite panels with the above attributes in mind, which also benefits from enhanced transverse stiffness. These panels have a central aluminium honeycomb core, which is sandwiched between two layers of glass or polycarbonate sheets. The aluminium core is glued to the external transparent sheets and gives a fish-eye effect to the outer surface of the panel and hence the combination gives a translucent product with a great aesthetic value as well as structural conformity. The question however remains as what is the thermal performance of these panels while the connecting member of the two faces is aluminium, which is one of the best conductors. The effect of the enhanced quality of these composite panels is investigated to confirm whether for a given characteristic of varying honeycomb web thickness and material properties, these products may be recommended as a replacement to the existing structures. This study explores the heat transfer characteristic of a complex heat flow path that exists in these panels, achieved through Finite Element modelling and experimental investigation; the convergence obtained in this study revealed that despite the existence of a highly conductive layer as the connecting membrane, these architectural composites were found to behave as fairly good insulators and could be used in parallel to the double glazed units.

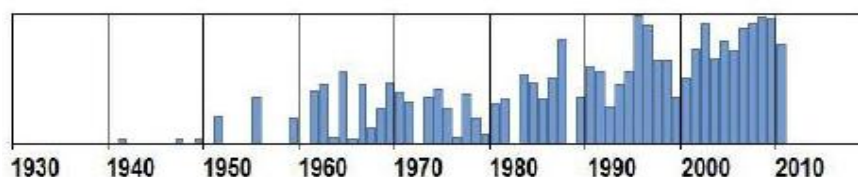
Keywords: Honeycomb Composites, Double Glazed Insulations, Finite Element Analysis, Architectural Panels, Fin Structural System

I. Introduction

Sustainability and elegance of the designs are two of the most important factors to consider in construction industry. In order to gratify these measures, engineers have introduced composite structures to the industry, simply by combining two or more of the traditionally used materials in one structure.

In the history of composite materials, the last decade has been the most momentous as the improvements have made applications such as bridge repair, bridge design, structural strengthening and stand-alone components possible. The use of composite panels in the UK has rapidly increased since the World War II; the development of their use in the industry is shown against the time in Figure 1.

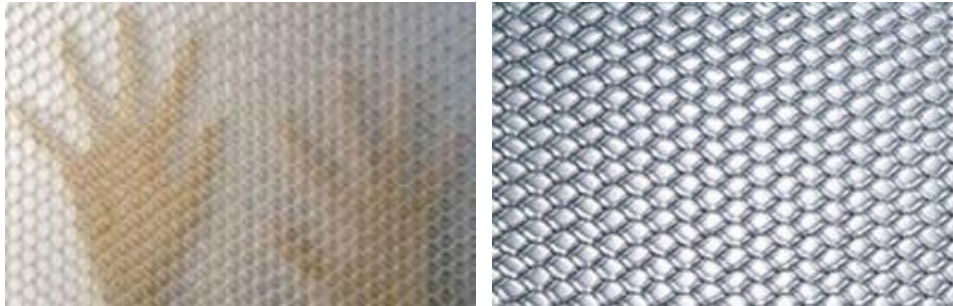
Figure 1 use of Composites in the UK between 1930-2010 [1]



Sales of composite panels increased despite an overall slowdown in the construction of industrial buildings, especially in Europe. In Britain, composite panels have increased penetration of the total cladding market from 41% in 2000 to 43% in 2001. Sales in Central Europe have also increased by 25% [1].

Amongst the manufacturer of composite panels, Encocam Ltd (Mykon) has developed an innovative sandwich composite panel, which has been designed specifically to suit the architectural purposes. The product is a composite with aluminium honeycomb as the internal core and glass or polycarbonate sheets as the outer skins. The aluminium honeycomb is the bonding material between the two outer skins, and is positioned perpendicular to the outer layers and provides an aesthetically pleasing product (Figure 2).

Figure 2 Architectural Honeycomb Composite is Translucent [2]



From the architectural point of view, the aesthetic value of the honeycomb sandwich panels makes them suitable for use as partitions, conservatory windows, floor tiles, doors, etc. and this makes the evaluation of the environmental characteristics of these panels more significant. The honeycomb architectural composite may have aesthetic advantages over the normal double glazed panels; however there will be a debate concerning their insulating properties. The existence of a layer of superconductive aluminium as the central layer, suggests the assumption that the aluminium honeycomb composites would not benefit from adequate insulating properties and will be defeated by the commonly used double glazed units.

The domain extent of this research is therefore restricted to finding the thermal behaviour of these honeycomb composite panels. Thermal analysis of such composites is difficult due to the complex three-dimensional nature of the heat conduction path through non-homogeneous materials, which is caused as a result of the bonding between two high modulus, high strength facing sheets with the low-density core material of aluminium.

II. Heat Management in Complex Equipments

Temperature is a measure of the average speed of molecular motion and according to the latest theories, heat energy or temperature is known to be caused by the vibration of the particles of every substance [3]. Therefore, heat is a form of energy that can cross the boundaries of both closed and open systems, but is not categorised as a property of the material.

In most thermodynamic situations, including the case of this research, the transfer of heat happens in the form of a combination of two or all three of modes of conduction, convection and radiation [4]; and even though these three modes have different applications, they all rely on a temperature difference in order to transfer between two systems. In cases where the architectural composite panels are used as an internal building component, such as partitions or floor tiles, the opposed heat will be transferred mainly due to convection on the external surfaces and conduction through the components of the panel. However, in cases where they are used as windows, conservatory panels or other external sections, radiation plays a key role in transferring the heat through to the other side.

The thermal management of a complex system made up of various components or sub-systems is not straight forward and one of the ways to analyse them effectively is by carefully dividing the entire system into different structural levels; the core, which consists of a thin hexagonal aluminium honeycomb cell and the external glass or polycarbonate sheets which isolate the core. The primary function of the outer skins is to protect the core from the atmosphere and environmental effects such as rust and corrosion. The adhesive which bonds these layers together is also housed within the package; however in most systems, this layer is too thin compared to the other members and has very small or no effect on the heat transfer through the composite and can therefore be ignored in calculations.

The speed of molecular motion in substances is reduced from gas to liquid and solid; in metallic solids such as the aluminium honeycomb core, the free and mobile electrons have the major role in transferring the heat, rather than the atomic vibrations which have minor contribution in this process; this makes metals the best conductors of heat energy according to the Fourier's Law of Conduction (Equation 1).

$$Q = kA \cdot \frac{\delta T}{\delta x} \quad [1]$$

The thermal conductivity (k) of materials is dependent on the temperature of that object and changes with temperature fluctuations. The higher the thermal conductivity, the more conductive the object is and transfers more heat. The average value of thermal conductivities of the components within these composites is evaluated based on the experimentally acquired temperature difference on either sides of every module.

In Fourier's Law of Conduction, δx is representative of the material thickness and due to its inverse relationship to the heat transfer, if this thickness is negligible compared to width and height of that panel, the heat conduction is assumed to occur only in the direction of the thickness [5]. This indicates that in calculating the thermal conductivity of the aluminium core, heat conduction is to be taken in the direction of the aluminium thickness only.

In order to keep a fluid at a constant temperature, there is a need to circulate this fluid. This is done through a fluid replacement process, which can be done either by Natural or Forced Convections.

In heat transfer terminology, where the surface of an object of temperature T_s happens to be in contact with a fluid of temperature T_∞ , the heat energy transfers between the two bodies, and is referred to as convection heat transfer, which is governed by Equation 2. As a result, a boundary layer is created adjacent to the surface, which is known as the Thermal Boundary Layer [6]. The temperature of the fluid in this layer fluctuates, as it tends to vary between the temperature of the surface and the temperature of the rest of the fluid.

$$Q = hA \cdot \delta T \quad [2]$$

Heating a fluid will cause the warmer molecules to become lighter than the surrounding fluid and rise. The consequent temperature mismatch within the fluid shall be circulated through a fluid replacement process

In order to measure the true behaviour of heat transfer through the composite panels under investigation, numbers of experimental tests have been carried out. The results indicated that despite the highly conductive aluminium honeycomb core, which is the link between the two outer surfaces, these composite panels are relatively good insulators.

It is therefore assumed that conduction through aluminium has very little or no effect in transferring the heat from one side to the other. Hence, due to the specific geometry and the aspect ratio of the aluminium core in these panels, it was assumed that the heat transfer in these composites is happening similar to conductive systems where fins are present.

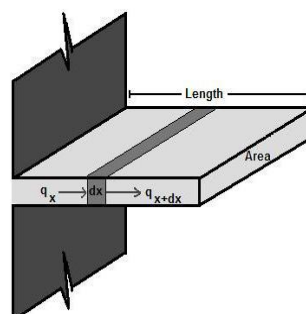
III. Heat Transfer from Extended Surfaces

In heat transfer process between a fluid and a solid surface, the heat flow depends on three main factors of contact surface area, temperature difference and finally the convective heat transfer coefficient. If in a system the base area is increased, it will form an extended surface or a fin, which provides additional convection area for the heat, which is conducted into the fin at its base.

Finned structures come to use when the existing surface area is insufficient for transferring the required quantity of heat and hence an extended surface is required to transfer the oncoming temperature.

The heat transfer that happens in the fin systems comprises of both conduction and convection heat transfers. However the convective heat transfer in the fins occur perpendicular to the direction of the conduction. The process of heat transfer in a fin structure is therefore known as combined conduction-convection system. If the fin, which is used in a system, has a finite length, it can be proven by the algebraic equations shown below, that the heat will transfer by convection to the surrounding fluid and will not reach the third surface by conduction [6]. The area "A" in equation 2 corresponds to the convection surface area, which in the case of fin structures is the cross sectional area of the tip of the fin (Figure 3).

Figure 3 One-dimensional Heat Transfer through a Rectangular Fin



The equation of the energy, which has entered the fin from its external face on the left side, is given by Equation 3. The input energy travels through the length of the fin ($d+dx$), and the energy, which goes out from right face, is given by Equation 4.

$$q_x = -k \cdot A \cdot \left(\frac{\delta T}{\delta x} \right) \quad [3]$$

$$q_{x+\delta x} = -k \cdot A \cdot \left. \frac{\delta T}{\delta x} \right|_{x+\delta x} = -k \cdot A \cdot \left(\frac{\delta T}{\delta x} + \frac{\delta^2 T}{\delta x^2} \right) \quad [4]$$

During this process, the energy, which is lost by convection, can be written as in Equation 5. It is essential to note that for convective heat transfer through the fin, the differential surface area will be a function of the perimeter of the fin (P) and the differential length (δx). Hence the energy balance equation is expressed as Equation 6.

$$q = h \cdot P \cdot \delta x \cdot (\delta T) \quad [5]$$

$$\left(\frac{\delta^2 T}{\delta x^2} + \frac{hP}{kA} \right) \cdot (T - T_\infty) = 0 \quad [6]$$

Where h is the convective heat transfer coefficient, L is the length of fin in millimetres, and T and T_∞ represent the ultimate temperatures at both ends. By replacing $(T - T_\infty)$ by θ and hP/kA by m^2 in the above equation, the general solution of the equation can be written as Equation 7.

$$\theta(x) = C_1 \cdot \cosh m(L - x) + C_2 \cdot \sinh m(L - x) \quad [7]$$

There are three possible boundary conditions in which these formulas could be applied to [7]. The boundary condition, which applies to the case of this research, followed by the consequent derived formulas, are summarised in Figure 4.

Figure 4 Formulation Summary for Fin Structures with Infinite Length and Convection at the Tip

$$T = \frac{T_\infty + (T_0 - T_\infty) \times \cosh(m \times (L - x)) + ((h/km) \times \sinh(m \times (L - x)))}{(\cosh(mL) + (h/km) \times \sinh(mL))}$$

↓

$$T = \frac{30 + 12.34 \times \cosh(0.048 \times (14 - x)) + (0.0017 \times \sinh(0.048 \times (14 - x)))}{(\cosh(0.658) + (0.0017 \times \sinh(0.658)))}$$

Note: x increasing by 0.23

IV. Fin with Convection at the Tip (h_c) Formulation

This case considers the situation where the fin has a finite length and in addition to the main body, the heat could also be released to the surrounding air by convection from the tip of the fin. The boundary conditions for such case are:

$$\text{At } x = 0 \quad \theta(x) = T_0 - T_\infty = \theta_0 \quad [8]$$

$$\text{At } x = L \quad k \frac{\delta \theta}{\delta x} + h_c \theta(x) = 0 \quad [9]$$

By placing these boundary conditions in Equation 7 and simplifying the integrations, the general solution of above equation can be written as:

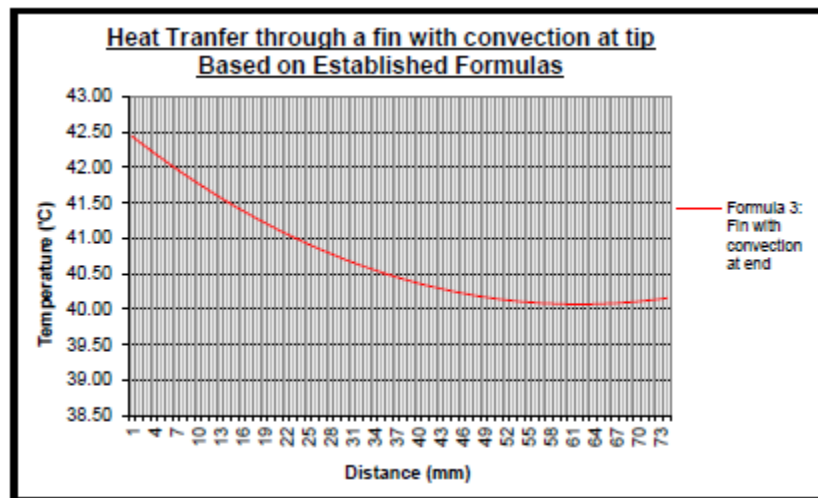
$$\frac{\theta(x)}{\theta_0} = \frac{T(x) - T_\infty}{T_0 - T_\infty} = \frac{\cosh m(L-x) + \frac{C_1}{C_2} \cdot \sinh m(L-x)}{\theta_0 / C_1} \quad [10]$$

Hence,

$$T = (T_0 - T_\infty) \frac{\cosh m(L-x) + \frac{h_c}{km} \cdot \sinh m(L-x)}{\cosh mL + \frac{h_c}{km} \cdot \sinh mL} \quad [11]$$

This equation, which summarised and illustrated in Figure 4 is plotted for given values of x , starting from 0, increasing every 0.23mm; the interval has been chosen based on the nodal distance in the FE model (Figure 5).

Figure 5 Curve of a Fin with Convection at Tip



V. Finite Element Analysis

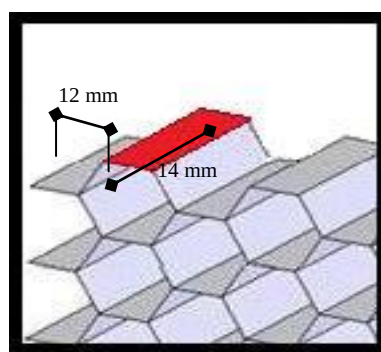
The theoretical investigations and assumptions used for analysing the heat transfer of these composite panels are compared to a realistic 3D Finite Element geometries modelled in ANSYS.

The initial domain extent was restricted to modelling the main areas of concern, without taking the details into account, and covering only the components which have a major role in heat transmittance. Hence instead of modelling the whole detailed geometry of the honeycomb, the geometry was simplified down to creating a 3D plate (Figure 6). The simplified model is easily comparable to the theoretical calculations, and the converged results obtained from this simplified model, validates the assumptions made and hence the same principles could be used to create the actual geometry.

The samples under investigation are made of sheets of toughened glass membrane with 8mm and 4mm thickness, or polycarbonate sheets of 4mm thickness. The aluminium core cell sizes may vary to suit different applications but was kept constant for the purpose of this study. The standard dimensions in which these panels are manufactured vary to a range of 27-100mm thick, 1500mm (Maximum) wide and a maximum length of 3000mm. However, for the purpose of this research, these panels were cut into a specific size to complement the required dimensions of the prepared test-rig; the panels of glass as the exterior membrane are 3400mm×3200mm×26mm and those with polycarbonate exterior membrane are 3400mm×3200mm×22mm.

The geometry of the initial model is restricted to a single plate of 12mm x 14mm, which represents one edge of the hexagonal cell and is to be compared to a fin structure. The dimensions are based on Cartesian Global Coordinate System, with X, Y, and Z-axes. It is assumed that no external layers exist, and therefore the temperature is applied directly on the side of the plate to monitor its distribution along the plate/fin.

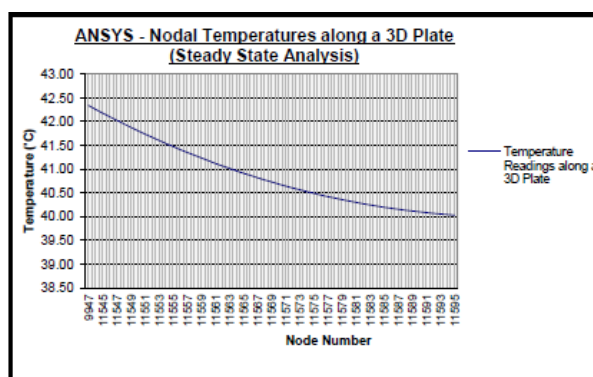
Figure 6 Single plate-One Edge of Honeycomb Aluminium Core



To perform a steady-state thermal analysis using ANSYS, the software has about forty elements for both 2D and 3D modelling including shell and solid models. From the available element Types, SOLID 70 (Brick, 8-node) is used, as it has a 3-D thermal conduction capability. The element has eight nodes with a single degree of freedom (temperature) at each node. The element is applicable to a 3-D, steady-state or transient thermal analysis” [8].

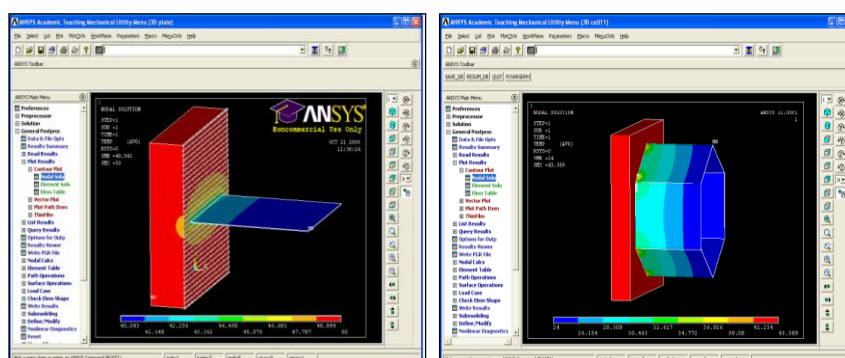
For the purpose of this research, the nodal solutions (nodal temperature) of the centre line of the plate were monitored. The results indicated that the temperature distribution along the plate is reduced through its length. The temperature readings are shown against their node numbers in Figure 7.

Figure 7 Nodal-Temperature against Node Number (Single Plate Model)



Comparing the graphs shown in Figures 5 and 7, it is evident that there is a gradual fall in the temperature as we proceed through the length of the plate, and the gradient asymptotically approach zero, towards the end of the fin/plate lengths.

Figure 8 Development of Geometry in ANSYS

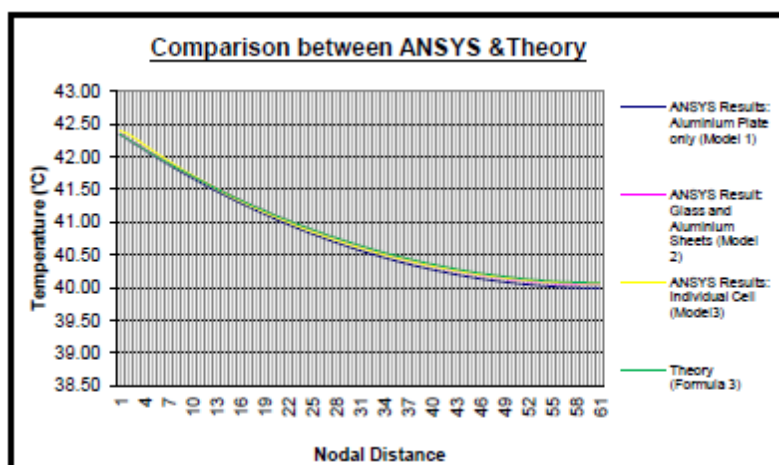


Since this initial model is very basic, the temperature distribution was recorded through developed geometries created in ANSYS, by initially adding a solid layer to represent the composite external sheet (Figure 8a), and finally developing the plate into a single hexagonal cell of the composite panel (Figure 8b).

The convergence of the nodal temperatures of all three geometries created in ANSYS with the theoretically established formulas of a fin structures (Figure 9), proves the validity of this research’s hypothesis, which claimed

the conduction heat transfer through aluminium has little or no effect in the heat transfer from one side to the other side of the honeycomb composite panel.

Figure 9 Comparison between ANSYS Results and the Theory of Fin Structures



VI. Concluding Remarks

From The insulating properties of both structural and architectural panels are becoming of increased significance in order to ensure building safety as well as minimising the costs of maintenance and insurance.

Architectural honeycomb panels have all of the desirable characteristics of a normal architectural panel such as aesthetic values, economy and vast application such as partition walls, windows, doors, floor tiles, etc. However, in addition to the mentioned characteristics, the thermal performance of these panels are of great importance as they are compared to similar architectural panels such as double-glazed units.

The honeycomb architectural composite have aesthetic advantages over the normal double glazed panels; nevertheless there will be a competition between the insulating properties of the two panels. The existence of a layer of aluminium as a perfect conductor suggests the assumption that the aluminium honeycomb composites are not a viable option in providing insulating properties. It was however the hypothesis of this research that despite the existence of super-conductor aluminium in the composite's combination, the low aspect ratio of this layer makes it inconsequential in defining the overall insulating properties of the composite. It was therefore assumed that the system of such composites could be compared to that of the fin structures.

The composite panels in question were tested through a designed test-rig, where the temperatures of all of the layers of the panel were monitored and recorded. The results from the test were imported and used for rigorous Finite Element Analysis using ANSYS. The temperature distribution through the composite geometry was compared to the established fin-structures' formulas. The convergence obtained in this study proves that despite the first assumption that highly conductive aluminium (which forms the central layer of the honeycomb architectural panels) will cause the panel to transfer a great deal of heat and act as a poor insulator, these architectural composites provides good insulating properties and could be used in parallel to the double glazed units.

VII. References

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