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Polymeric Numerical Model and Parametric Study on Heat transfer in Sandwich and Stringer Panel Systems

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Abstract
Numerical analyses play an important role in today's research. Although they cannot always be a complete substitute for testing or other practical methods, they are important supplements to deepen our understanding of an existing material or to explore a subject in depth. A computer program has been developed at the University of Texas to calculate temperature distributions within a GRP structure when exposed to fire attack. This paper will discuss the behaviour of GRP at high temperatures and the theory behind the heat transfer program. This paper also reviews a number of different polymeric numerical heat transfer models by other researchers. Finally, a series of parametric studies will be presented to demonstrate the practical use of this computer program.
Keywords: heat transfer; sandwich panel; GRP; temperature; model.

1. Introduction to GRP Behaviour in Fire

In order to model the heat transfer and thermal performance of a GRP laminate realistically, its basic behaviours under fire conditions must firstly be established. When exposed to fire, a GRP laminate will undergo both chemical and physical changes at different levels of heat flux. In the beginning, the heat flux from the fire source will be transferred through the laminate by transient heat conduction. The temperature will be less than 200-300°C and there is no chemical reaction. The temperature rise depends on the heat conduction rate into the material and the boundary conditions [1].

As the temperature rises to 200-300°C, pyrolysis occurs and creating gaseous products. The resin degrades to form a layer of char. This char layer will build up as the pyrolysis front moves further into the laminate. Due to its low thermal conductivity, the char forms a thermal barrier keeping the interior cool. Once the pyrolysis reaction is completed, the temperature of the laminate increases and heat transfer afterwards is by transient heat conduction, governed by the thermal properties of the remaining fibres [2].

When the surface temperature exceeds 1000°C, carbon-silica reactions occur in which the carbon residue from the pyrolysis reactions and the silica filler react chemically. Finally, as the temperature continues to rise, the residue char oxidises and erodes away, and the remaining glass fibres will eventually burn out.

Almost every mathematical model of combusting GRP laminate has been developed according to the above material decomposition behaviour. Most of the models deal with the decomposition process up to the completion of the pyrolysis reaction. The later stage of composite decomposition, e.g. carbon-silica reactions, is not of main interest as most of the material strength will be lost [3]. Many numerical models have been developed, each having its own assumptions and claiming to resemble the true decomposition scenario best.

1.1 Decomposition

Plastic materials are organic in nature and are inherently combustible, i.e. they will decompose or burn in a fire environment. At present, it is not possible to model this effect from basic chemical reactions. In the numerical models, decomposition is modelled using an Arrhenius equation (Eq. 2) to relate the mass loss to the heat of reaction.

1.2 Formation of Char

The formation of char in polymeric material is a complex process which depends on hydrodynamics together with physical and chemical interactions. Again, current models can only deal with the macroscopic behaviour without explaining the fundamental charring process. In the simple approach, a plastic composite is separated into rigid material and char, depending on the ratio of m/m_o where m is the remaining mass and m_o is the initial mass, obtained from a first order Arrhenius equation [4]. Some investigators have attempted to include different degrees of the charring process. This requires knowledge of the final density of the char in which the process might give rise to two problems in application. Firstly the precise definition of the final char status is difficult to establish. Also an additional expression for char pyrolysis will be required if it commences its final breakdown in the time zone of interest.

1.3 Delamination

Many experimental researchers experience loud 'bang' sounds when delaminations of composite laminates occur. This is particularly the case with phenolic resins. It is believed that delamination is caused by the increasing internal pressure due to vaporisation of the chemically bonded water in the resin when the temperature rises to over 100°C. The water vapour is initially trapped within the composite matrix owing to its low permeability and attains very high internal pressures upon heating the laminate. At about 200°C, a sudden release of high pressure can tear the laminate. Due to delamination, the mechanism of heat transfer from the hot (exposed) side to the cold (unexposed) side is altered. Before the incident, heat transmission is only by conduction. However, after delamination heat transmission depends on radiation and convection in the gaps. The simple approach is to adopt a single value of temperature of delamination [5].

1.4 Moisture Content

The heat transfer rate in a hygroscopic material is influenced significantly by moisture evaporation [6]. In the context of the present research, this effect can be significant with certain facing materials, such as the gypsum board. Moisture content is in the form of chemically or physically trapped water. The mechanism of the combined heat and moisture transfer is a function of temperature, moisture distributions, chemical reactions, multiphase mass transfer, permeability and non-linear material properties. During the heating of a hygroscopic material, a process of dissociation (dehydration), vaporization and migration of moisture take place. Energy is needed to evaporate the moisture, to break the chemical bond of water and to absorb free water from the material. The simple approach is to convert these energies into additional specific heat of the material.

2. Theory and Formulations of a Numerical Heat Transfer Model for Polymeric Materials

2.1 The Mathematical Model

The section will discuss the GRP-specific features of a mathematical model and the formulations used in a two-dimensional finite element based numerical heat transfer model [7]. The model is mathematically simple, yet it can capture the main features of the pyrolysis process and the consequent heat transfer behaviour. The following idealisations have been adopted:

• The GRP material is assumed to be homogenous and the transport of heat and mass is perpendicular to the face of a panel so that the problem is assumed to be one-dimensional.

• There is a thermal equilibrium between the decomposition gases and the solid material but there is no accumulation of these volatile gases in the solid material.

• The feedback of the heat released by the flames of the combustible volatiles back to the panel in a small scale post-flashover fire furnace test is neglected owing to its relatively small contribution compared with the enormous heat flux created by the furnace.

Following the principles of the conservation of mass and energy, the one-dimensional energy equation in a panel undergoing thermal decomposition, pyrolysed convection, and energy sink due to pyrolysis, is [8]:

$$\frac{\partial}{\partial t}(\rho h) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{\partial}{\partial x}(m_g h_g) - Q\frac{\partial \rho}{\partial t} \qquad 1$$

where ρ is the density (kg/m³)
       h is the enthalpy (J/kg)
       t is the time in seconds
       T is the temperature (K)
       k is the thermal conductivity (W/mK)
       x is the spatial variable (m)
       h_g is the enthalpy of gas (J/kg)
       m_g is the mass flux of gas (kg/m²s)
       Q is the heat of decomposition (J/kg)

The rate of decomposition of the resin is assumed to conform to a mean reaction which is described by a single first-order Arrhenius function:

$$\frac{d\rho_r}{dt} = -A\rho_r \exp\left(\frac{-E_A}{RT}\right) \qquad 2$$

where ρ_r is the instantaneous density of the partially pyrolysed resin
      E_A is the activation energy (J/mol)
      R is the gas constant (8.314 J/K.mol)
      T is the temperature (K)
      A is the pre-exponential factor (s⁻¹)

Resin pyrolysis is assumed to be one way until it is totally consumed. If the accumulation of gasses is ignored, the conservation of mass may be written as:

$$\frac{\partial m_g}{\partial x} = -\frac{\partial \rho}{\partial t} \qquad 3$$

where the mass flux, m_g, at any spatial location and time can be calculated by integration of Equation 3.

Equation 1 can be modified by expanding the first three terms, and substituting in the specific heat and the continuity equations. After rearranging, Eq. 3.1 becomes:

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} - m_g C_{pg}\frac{\partial T}{\partial x} - \frac{\partial \rho}{\partial t}(Q + h - h_g) \qquad 4$$

where C_p is the specific heat of the material at constant pressure (J/kg°C)
      C_{pg} is the specific heat of gas at constant pressure (J/kg°C)

2.2 Thermal and Transport Properties

The thermal response of a polymeric material is significantly sensitive to the stage of decomposition, i.e. the rate of density change. This is expected since the rate of energy consumption and the thermal and transport properties of the material are all functions of the rate of pyrolysis. The values of the pyrolysis reaction in Eq. 2 for kinetic parameters A and E_A will determine the intensity and duration of decomposition corresponding to a given intensity of heat flux. Since the in-situ measurement of A and E_A under the required thermal condition is difficult, the current practice is to estimate them by choosing reasonable values which give good agreement between theory and experiment. In Wang's model, for accurate modelling without making the model too complicated, two sets of values are assumed, for the hot (exposed) and the cold (unexposed) sections of the panel.

The variation of thermal conductivity also complicates the heat transfer pattern because it will change with both the temperature and the stage of decomposition. A simple expression for thermal conductivity is to assume a linear function of temperature, giving

$$k = k_o + \alpha T \qquad\qquad 5$$

where k_o is the thermal conductivity at ambient temperature. At the beginning of the heating process, α is negative, indicating a reduction in thermal conductivity due to the low conductivity of the char. As heating continues, the char will be oxidised and erode away, leaving the fibreglass alone. During this phase, α will be positive, giving an increase in thermal conductivity close to that of the crumbling glass mat. The specific heat of GRP is also assumed to be a linear function of temperature. Table 1 gives the thermal and transport properties of numerous materials [9].

2.3 Moisture Effect

In the heat transfer model, moisture evaporation is assumed to take place during a temperature interval of 85°C to 135°C and the latent heat energy of evaporation is added into the heat capacity of the material. The latent heat of evaporation is taken as 2.25×10^6 J/kg so that the additional specific heat is obtained from

$$DC_p = \frac{2.25\,x10^6\,e}{\Delta T}\ (\text{J/kg°C}) \qquad\qquad 6$$

where DC_p is the additional specific heat

e is the moisture content expressed as the percentage in weight

ΔT is the magnitude of the given temperature interval

In the case of gypsum boards, increasing the above value by a factor of 1.8 to include the effects of moisture movement and recondensation. The rate of temperature increase will be slowly reduced, but not halted, during this temperature interval. The advantage of this approach is that a gradual increase of temperature during vaporisation can be simulated.

Table 1 *Thermal and transport properties of composite materials*

Product	Thermal Conductivity Eq. 3.6 (W/m°C)	Specific Heat $C_p = C_o + C_1 T$ (J/kg°C)	Kinetic Parameters Eq. 3.2 $A(s^{-1})$, E_A(J/mol)	Heat of Decomposition (J/kg)
GR Polyester panel	$k_o = 0.26$ $\alpha_1 = -0.0001356$ $\alpha_2 = 0.002$	$C_o = 1200$ $C_1 = 0.8$	*Cellulosic Fire*: $A = 1200\ [400]$ $E_A = 54000\ [70000]$ *Hydrocarbon Fire*: $A = 1200\ [600]$ $E_A = 54000\ [68000]$	-2500000
Ameron pipes (epoxy resin)	$k_o = 0.24$ $\alpha_1 = 0$ $\alpha_2 = 0.0012$	$C_o = 1270$ $C_1 = 0.23$	*Cellulosic Fire*: $A = 800$ $E_A = 56000$ *Hydrocarbon Fire*: $A = 1200$ $E_A = 52000$	-30000
Phenolic laminates	$k_o = 0.28$ $\alpha_1 = 0$ $\alpha_2 = 0.0018$	$C_o = 1300$ $C_1 = 0.3$	*Hydrocarbon Fire*: $A = 1200\ [600]$ $E_A = 60000\ [58000]$	-1600000

Vermiculux	$k_o = 0.28$ $\alpha_1 = -0.00008$ $\alpha_2 = 0$	$C_o = 800$ $C_1 = 0.2$	N/A	N/A
Voidfill 7D	$k_o = 0.0396$ $\alpha_1 = -0.00012$ $\alpha_2 = 0$	$C_o = 1470$ $C_1 = 0$	N/A	N/A
Gypsum board	$k_o = 0.24$ $\alpha_1 = 0$	$C_o = 950$ $C_1 = 0$	N/A	N/A

The thermal conductivity values in Table 1 are for dry materials. The value of the thermal conductivity will increase as temperature increases under conditions of constant moisture content. On the other hand, the moisture content is gradually reduced as a fire test progresses. The resultant thermal conductivity therefore is assumed to arise as a combination of both effects. The general equation considering the effect of moisture content on thermal conductivity can be expressed as:

$$k(M) = k(o) \times f(M) \tag{7}$$

where $k(o), k(M)$ is the thermal conductivity values at o and M moisture content in volume respectively

$f(M)$ is an empirical factor

Jakob (1949) recommended empirical factors $f(M)$ for masonry or similar materials, allowing the conductivity $k(M)$ of a moist material to be estimated for any moisture level when the thermal conductivity is known for a given moisture content:

$$f(M) = 1.0891 + 0.17675\,M - 8.7812\,x10^{-3}\,M^2 + 1.7617\,x10^{-5}\,M^3 \tag{8}$$

Since the thermal properties, i.e. thermal conductivity, specific heat, emissivity and charring rate, of building materials vary to a greater or lesser extent with temperature, there is very little information available regarding the actual values to be used in analysis [9,10]. The thermal properties of most materials relevant to this study are unknown and the experimental measurements of these properties are complicated and time consuming. Previous researchers have assumed the initial values using the information supplied by the manufacturer. These values were then refined by fitting them to some representative fire tests. The numerical solution using this approach provides a good agreement with the experimental results [11,12]. Numerous models have been generated by the author to verify the heat transfer program and to look at the temperature profiles of composite materials in the forms of sandwich or stringer wall panels [13]. The results from these numerical models will be presented in the next section.

**3 Examples of Using Numerical Heat Transfer Analysis for Polymeric Materials**
This section will present the results of some examples of numerical simulations using the heat transfer program. This numerical study is intended to demonstrate the important parameters of heat transfer in polymeric materials. Detailed results used in the validation of the program tested on four GRP panels:
- Specimen 1: Sandwich panel
Phenolic laminates as skin, mineral wool as core
- Specimen 2: Sandwich panel
Gypsum boards as skin, mineral wool as core
- Specimen 3: Stringer wall panel
Phenolic laminates as skin, mineral wool as core and GRP C-channel as strut
- Specimen 4: Stringer wall panel
Gypsum boards as skin, mineral wool as core and GRP C-channel as strut

Figure 1 shows the dimensions of these four specimens. The fire tests were conducted in the 1.5 x 1.5 x 1.5 m furnace at the University of Texas by subjecting the specimens to the standard BS476 fire exposure on one side. Figure 2 shows the locations of the thermocouples.
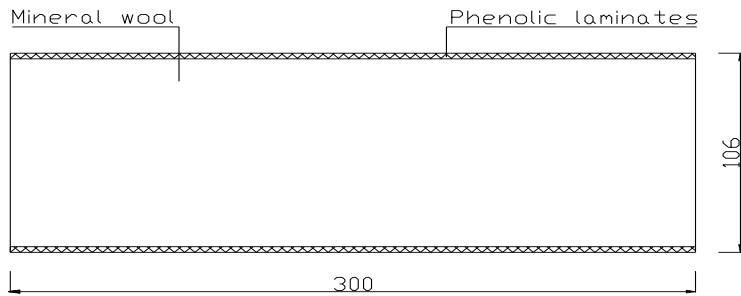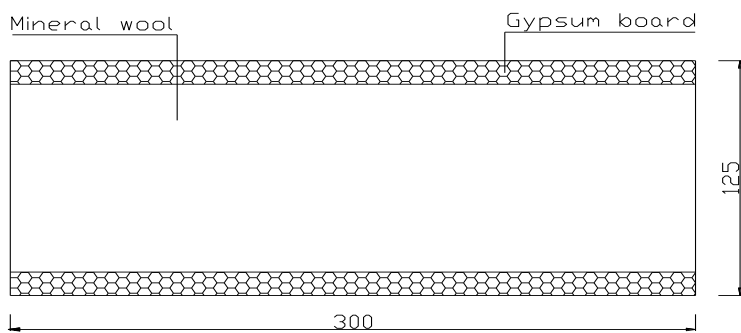
Mineral wool   Phenolic laminates

106

300

(a) Specimen 1: Sandwich panel, Phenolic laminates, mineral wool core

Mineral wool   Gypsum board

125

300

(b) Specimen 2: Sandwich panel, gypsum boards, mineral wool core

Mineral wool GRP C-channel   Phenolic laminates

106

300
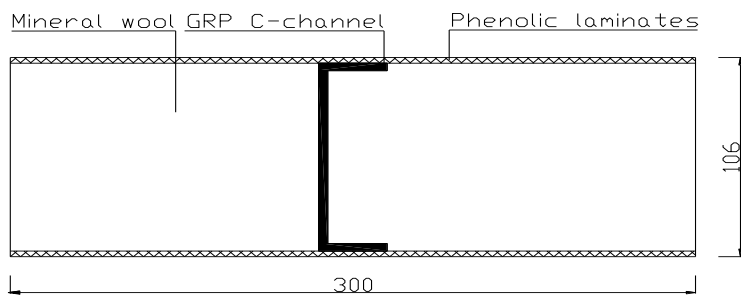
(c) Specimen 3: Stringer wall panel, GRP C-channel strut, Phenolic laminates, mineral wool core

Mineral Wool GRP C-channel   Gypsum board

125

300
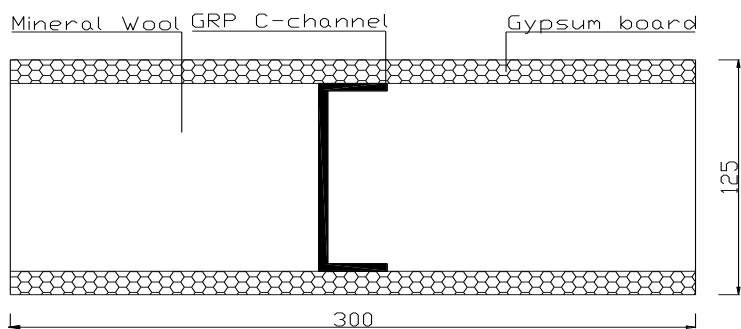
(d) Specimen 4: Stringer wall panel, GRP C-channel strut, gypsum boards, mineral wool core

**Figure 1** Specimens tested by Currie *et al.* (2001a)
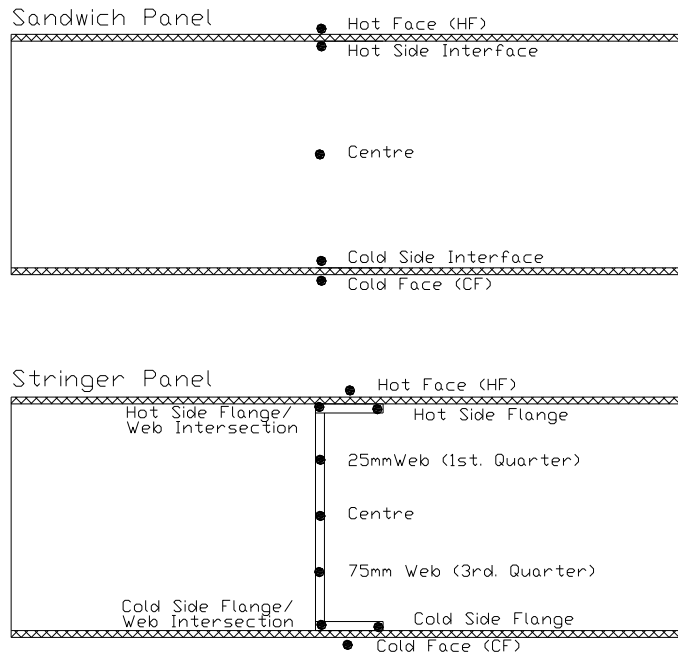
Figure 2 Exact location of thermocouple for sandwich and stringer wall panels
(Currie *et al.* 2001a)

Numerical heat transfer simulations were performed for different models of the test specimens. The first four models adopted the BS476 fire curve as the input fire source in the analysis. Figures 3(a)-3(b) compare the temperature-profiles between experimental (solid lines) and numerical results (dotted lines). Gypsum plasterboard has a high moisture content and when subjected to high temperatures energy sink will occur requiring extra energy to evaporate the moisture content. In the numerical simulations, the moisture in gypsum plaster is not included, resulting in higher temperatures.
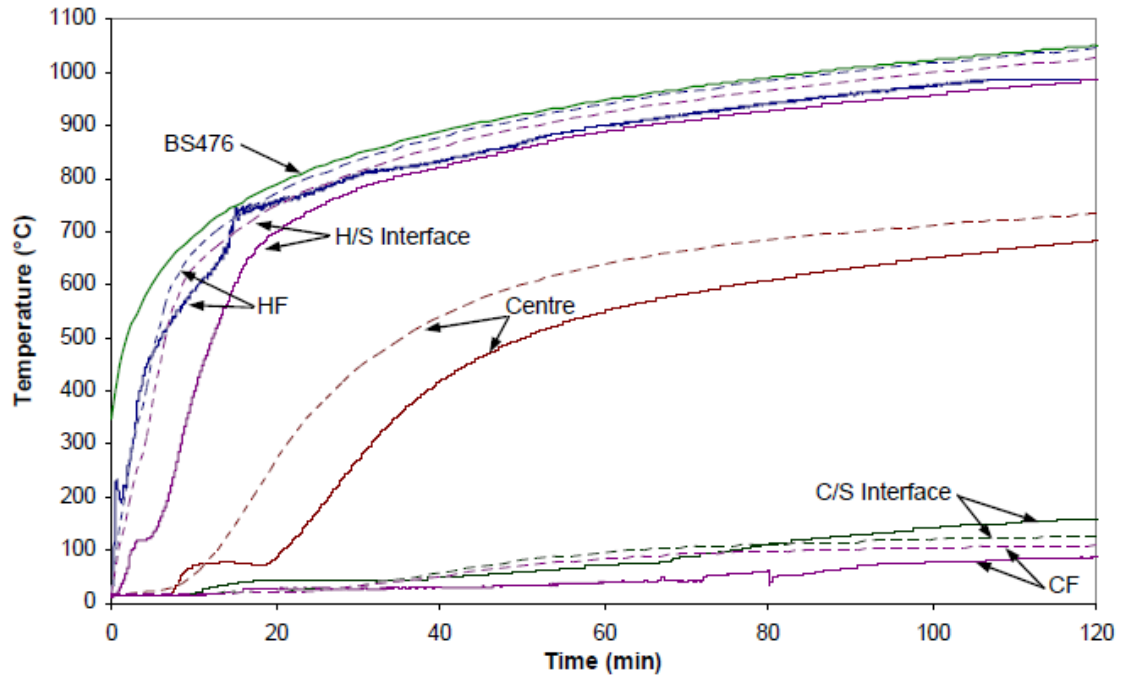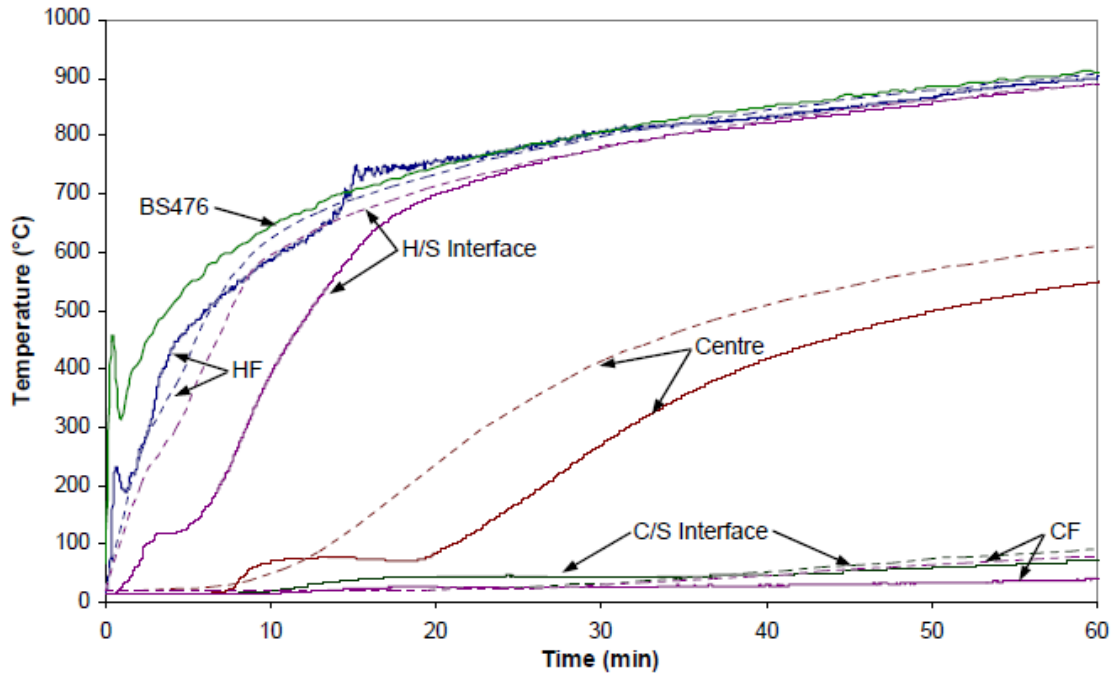
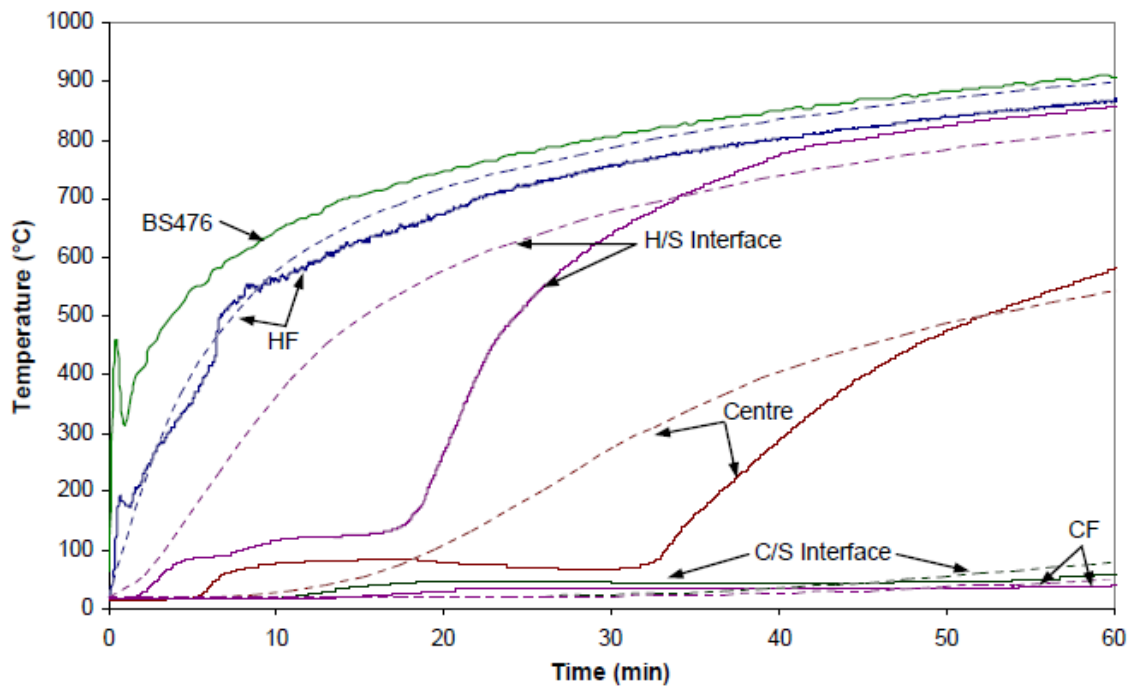**(a)** Specimen 1: Sandwich panel
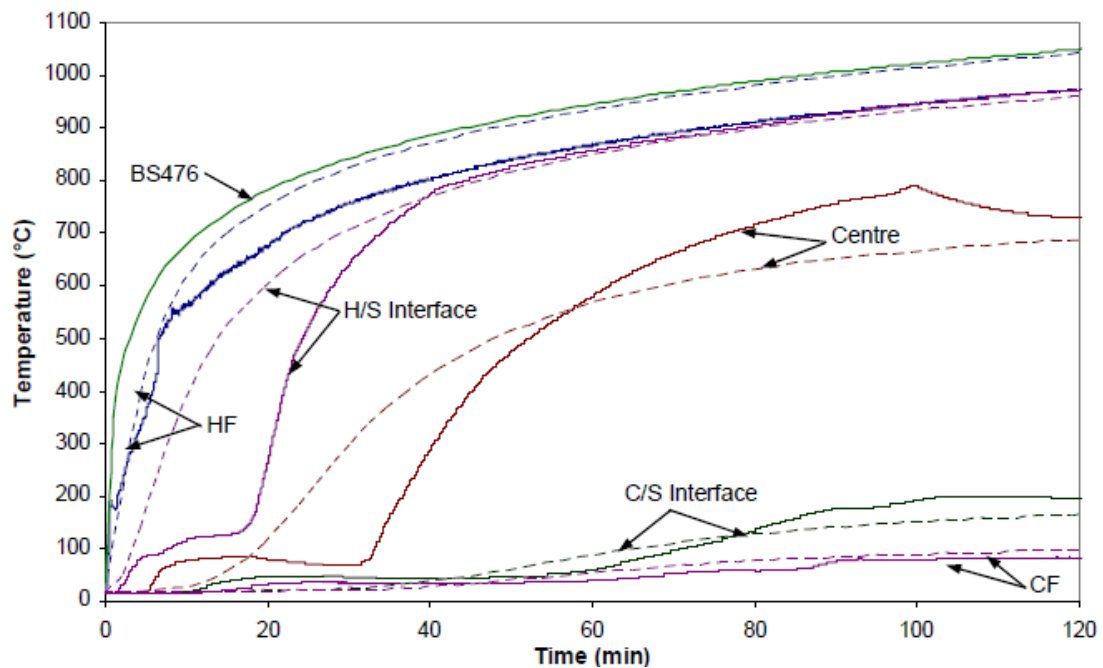
(b) Specimen 2: Sandwich panel

Figure 3 Measured and predicted temperature-time profiles of Specimens 1-4 BS476 fire curve as input, no moisture effects in gypsum boards

During fire tests, it was found that the measured furnace temperature was averagely 30°C lower than the specified values of the standard BS476 fire curve. In the next four models, the measured furnace temperatures were used as input in simulations. Figures 4(a)-4(d) compare simulations and test results. For clarity, temperature-time profiles at the 1st and 3rd quarters of the panel are excluded. Comparing the corresponding graphs (Figure 3 and Figure 4), it can be noticed that the predicted hot face temperatures were closer to the measured values when the actual furnace temperature was used as input.
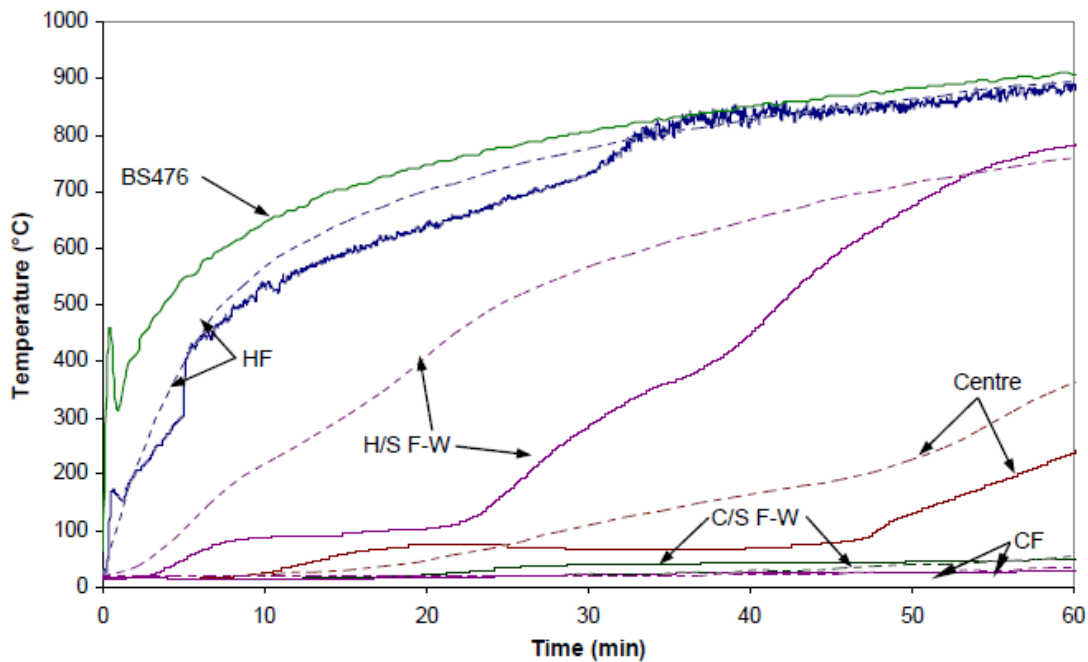
(a) Specimen 1: Sandwich panel

(b) Specimen 2: Sandwich panel
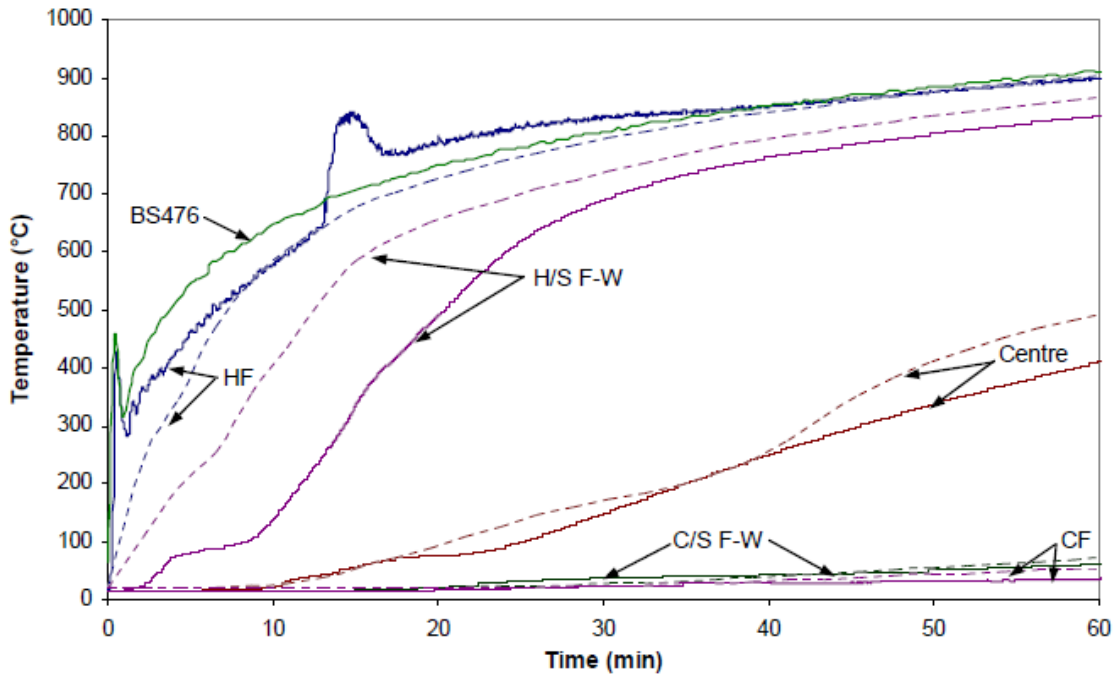
(c) Specimen 3: Stringer wall panel

(d) Specimen 4: Stringer wall panel
Figure 4 Measured and predicted temperature-time profiles of Specimens 1-4
Measured furnace temperatures as input, no moisture effects in gypsum boards

Further numerical simulations have been performed by taking into account moisture effects of the gypsum plasterboards. To do this, the specific heat and thermal conductivity of the gypsum were treated differently; the specific heat being increased sharply within the 85°C to 135°C region (determined using Eq. 6), while the thermal conductivity stayed constant up to 135°C and then being increased at a constant rate.

Figure 5 presents the results for specimens 2 & 4 where gypsum was used. The measured furnace temperatures were used as input in the analysis. As can be observed, the numerical profiles show the same trend of temperature rise compared to the experimental results. Temperature plateau regions are now noticeable from the numerical profiles although not as long as the

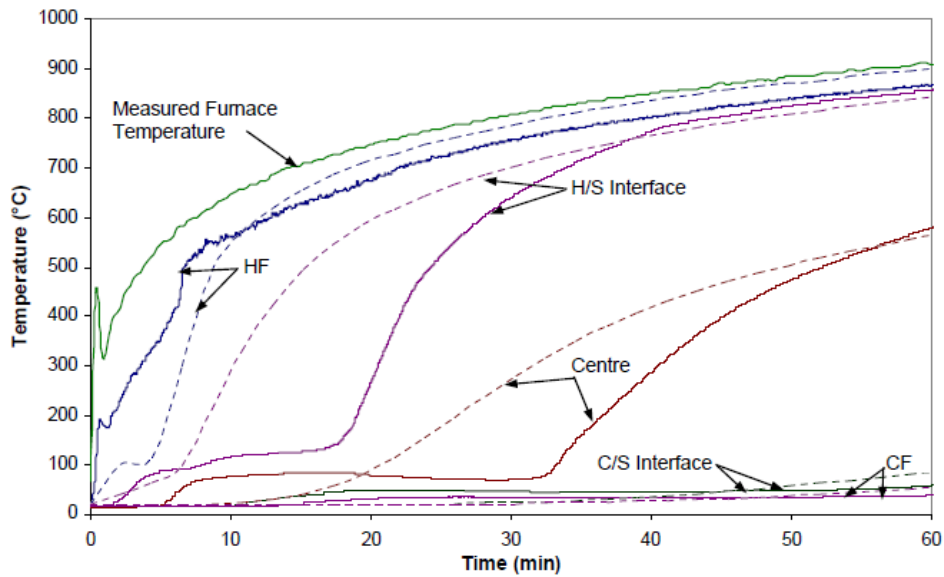experimental ones. Nevertheless, this gave improvement compared to the previous cases (Figure 3(b) and 4(d)).

Figure 5 Measured and predicted temperature-time profiles of Specimens 2. Measured furnace temperatures as input, consider moisture effects in gypsum boards

A possible factor influencing the accuracy of the numerical result is the thermal boundary conditions. To eliminate the uncertainties associated with this factor, two more models have been generated without any facing material on the exposed side. Figure 6 shows these modified panels schematically. Model (a) was generated to simulate test specimen 2 sandwich panels without the hot side. The measured board/mineral wool interface temperatures were taken as the input data in the analysis. The resulting temperature-time profiles are plotted in Figure 7. As expected, the predicted hot face temperature profile coincides with the input temperature. Temperatures at the centre of the panel were underestimated, which could be due to the low conductivity used for the mineral wool core. Nonetheless, the numerical results are much closer to the test values, indicating the importance of correctly considering the thermal boundary condition.
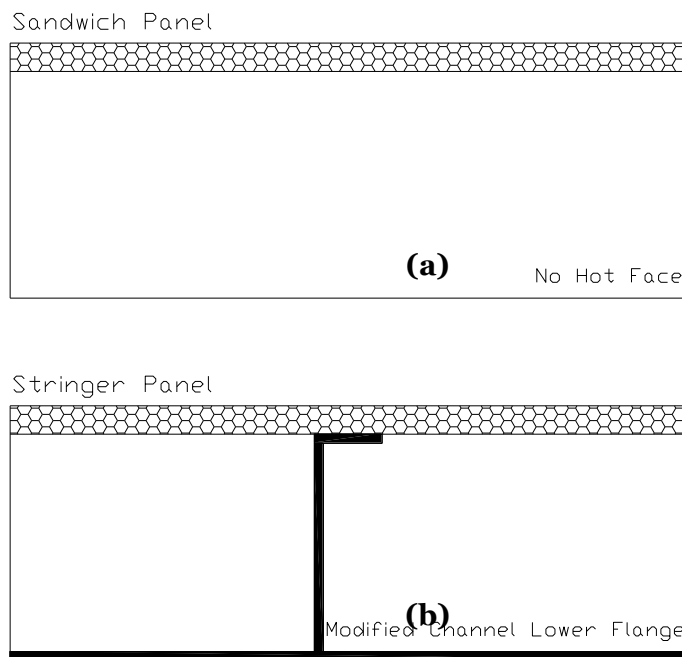

Figure 6 Sandwich panel and stringer wall panel models with no hot faces
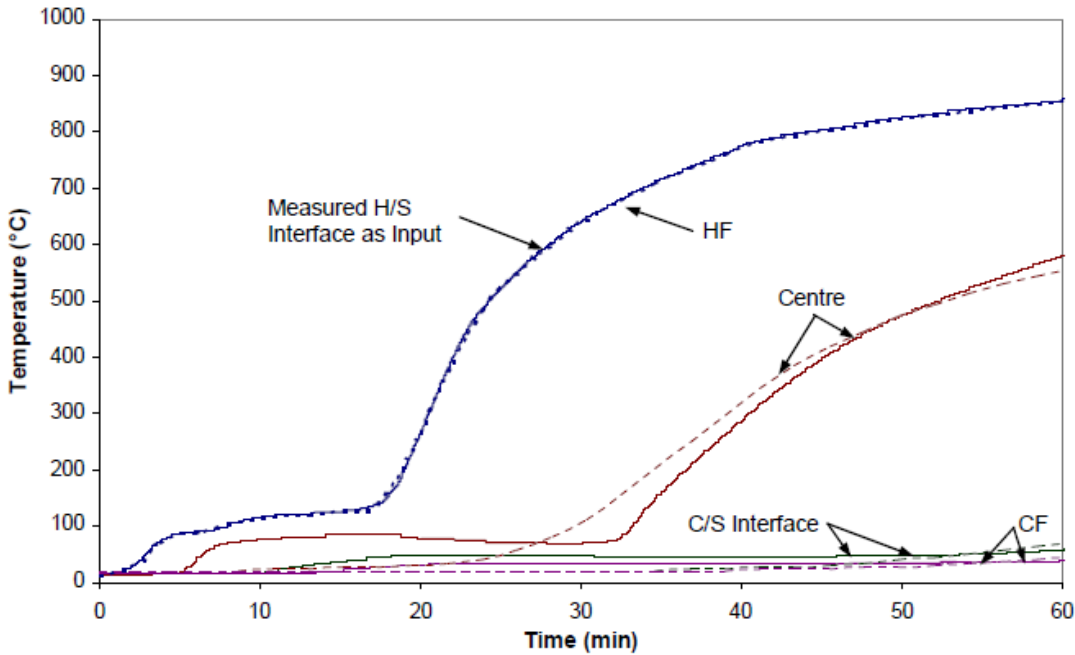
Figure 7 Measured and predicted temperature-time profiles of Specimen 2: Sandwich panel.
Measured hot side interface as input, no hot face

Model (b) deals with specimen 4 without the hot face. Due to numerical instability experienced using the program, the best alternative to simulating test specimen 4 without the hot face was to use a long lower flange for the channel (see Figure 6(b)). As far as heat transfer along the web of the channel is concerned, this condition should not incur high inaccuracy in the modelling. The measured temperatures at the flange/web intersection of the channel were taken as the input source in the analysis. Figure 8 shows the results of the modified panel. In general the model has slightly underestimated the temperatures within the panel. Nevertheless, the simulated results are quite satisfactory.
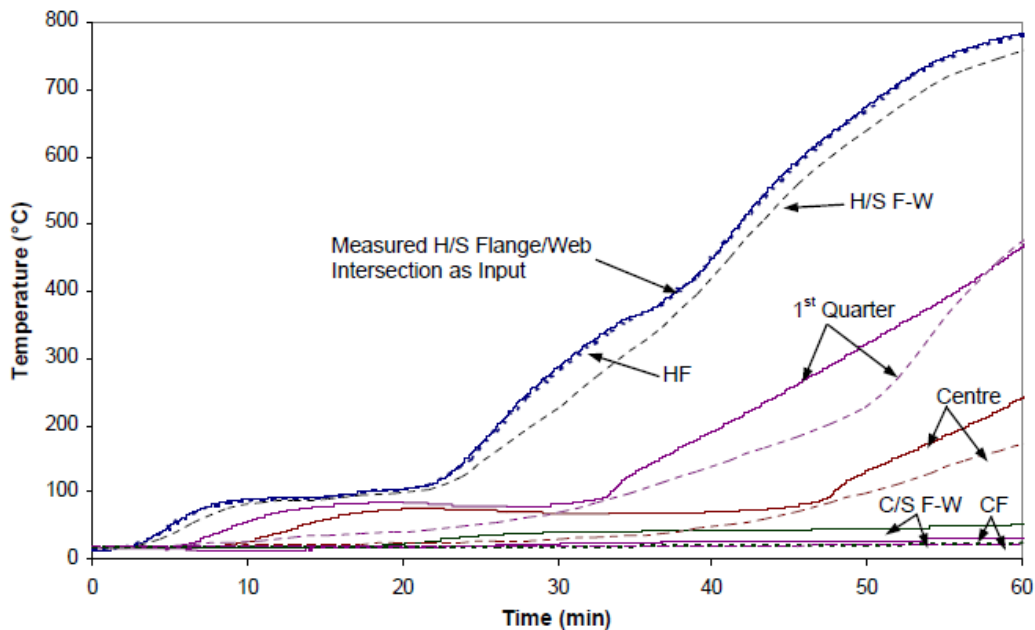

Figure 8 Measured and predicted temperature-time profiles of Specimen 4: Stringer panel.
Measured hot side channel flange/web intersection as input, no hot face

4. Conclusions

This paper has discussed the heat transfer analysis in GRP sandwich and stringer panels. Understanding the behaviours of polymeric material under fire is vital in developing a suitable numerical model from appropriate heat transfer simulations. This paper focused on a two-dimensional heat transfer analysis using finite element method. Numerous simulations were conducted based on the available test results. These simulations were performed to investigate the effects of changing material properties and to examine the accuracy of the analysis. In general, the two-dimensional FE heat transfer analysis is capable of giving useful results. However, the accuracy of these simulations still leaves a little to be desired and the user needs to be aware of its limitations. This comes about partly because the program deals with the complex phenomena in a simple way, i.e. treating heat and mass transfer in wet materials by adding a value to the specific heat of the dry materials, using a first order Arrhenius equation for charring of the polymeric material, neglecting the generation of volatiles and using simplistic treatment of delamination. Another important factor is the lack of the availability of accurate material information. Such information is difficult to find and manufacturers of different materials give, at best, only information at ambient temperature. In addition, the thermal boundary condition needs careful consideration. Whilst numerical heat transfer in fire is developing fast, for construction involving polymeric materials, it is still essential to carry out experiments with numerical tools providing supplementary extension of the test results.

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Полимерная вычислительная модель и параметрическое исследование теплопроводности систем сэндвич-панелей и панелей, подкрепленных стрингерами

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Аннотация. Многочисленные исследования играют важную роль в современных научных работах. Хотя они не могут полностью заменить апробацию или другие практические методы, они являются важными заменителями для улучшения нашего понимания существующего материала или для детального изучения предмета. В Техасском университете была разработана компьютерная программа для расчета температурных распределений в стеклопластиковых конструкциях во время пожара. В данной статье изучается поведение стеклопластика при высоких температурах и теория, лежащая в основе программы температурных распределений. В данной статье также рассматриваются различные полимерные вычислительные модели распределения температур, разработанные другими исследователями. В заключении представлен ряд параметрических исследований для демонстрации практического применения данной компьютерной программы.

Ключевые слова: температурные распределения; сэндвич-панели; стеклопластик; температура; модель.