Model for the Characterisation and Design of Passive Fire Protection (PFP) Systems for Steel Structures

A G Gibson, Wan Wan Jusoh, G Kotsikos, P. Di Modica, S. Christke
University of Newcastle upon Tyne
K. Yi, Chinese Aerospace Institute
A.P. Mouritz, E. Kandare, RMIT, Australia

This paper describes the use of a small-scale constant heat flux propane burner test to characterise PFP systems. Three such systems were investigated, each working on a slightly different principle. These were: (i) a refractory ceramic wool, (ii) a phenolic resin 'composite' containing porous ceramic prills, and (iii) a composite intumescent system. In each case the heat transferred through the PFP was measured by attaching it to a 10 mm thick steel substrate and measuring the temperature rise. In the present study the steel rear face was open to the atmosphere. It was found that, despite the different operating mechanisms of the three PFP systems, all showed similar substrate temperature-time profiles. This was characterised by an initial thermal lag followed by a period of near-constant heat flux, with a near-linear temperature rise.

It was found that the transmission of heat through each PFP could be modelled well by considering only the initial thermal lag due to thermal diffusivity (along with initial decomposition in cases (ii) and (ii), followed by a near steady-state period involving only heat conduction through an established refractory layer.
The solution involved coupling analytical expressions for the unsteady behaviour at the start of the test, followed by a 'lumped parameter' treatment of the later stages. The solution involves just two material parameters: an effective thermal diffusivity for the PFP near to the start of the fire exposure, along with an effective thermal conductivity relating to the PFP in its later stages. The approach leads to a simple design equation that can be used to characterise and design fire protection materials when using the well-known 'HP/A' procedure. Allowance can also be made for the effect of heat losses at the rear of the steel substrate.

1. Introduction

PFP materials[1-3] have been used for a long time and have major applications in structural engineering, the offshore industry[1], rail, aerospace and marine transport. Steel structures begin to lose functionality at temperature above 200ºC, while, with aluminium, the tolerable rise is about 100ºC.

Qualification procedures for the fire resistance of protected structures involve expensive large-scale testing, usually with furnaces or exposure to a jet of burning gas or liquid fuel. Furnace tests involve following a particular time-temperature profile often related to cellulosic or hydrocarbon fire exposure. The necessity of following such a temperature profile is also, of course, dictated by the fact that furnace are unable, generally, to heat up instantaneously.   Constant flux tests involving direct flame exposure are often, therefore preferred to furnace tests in the marine, offshore and aerospace industries. Surprisingly there are no commonly-used design equations that can be used to model the heat

transmission of particular PFP systems, the only available aid to design being the widely-used 'HP/A' approach.

In the present study the heat protection function of the laminate was simulated by bonding it to a 10 mm thick steel plate and recording the temperature rise of the plate. In the present case the rear face of the plate was not insulated, but left open to the air.

All three PFP materials studied will have exhibited complex heat transfer phenomena. The Kaowool mineral fibre insulation will have displayed the simplest behaviour, without any significant decomposition or intumescent processes. Nevertheless the thermal conductivity of the material, achieved by immobilisation of air pockets within the fibrous network, show a factor of 4 or more increase between room temperature and the hot face temperature in the test. In the case of the phenolic/ceramic prills system, there would have been an insulating effect from the ceramic prills, along with effects due to the decomposition of the phenolic binder. To model this fully it would have been necessary to carry out a full unsteady state analysis, using the Henderson Equation to take into account the effects of the endothermic resin decomposition process, along with the flow of decomposition gases[4]. The intumescent system would have been even more complex[2,3,5,6], involving the formation of a carbonaceous char, along with a factor of 10-20 expansion.

The present simplified approach assumes that with all three type of PFP a refractory layer of low thermal conductivity is established so that in the middle and later parts of the test the situation simplifies to heat conduction through this layer, with a near-constant heat flux, into the underlying metal substrate- as described by the 'lumper parameter' model.

The design approach proposed is applicable in any situation where a composite laminate is required to limit the heat flux into a structure to a stipulated value. In particular the procedure is compatible with the well-known 'HP/A' procedure that is widely used by structural engineers. In this procedure the heating effect that takes place when a protected structural section, such as an I-beam or other section can be determined from the thermal properties of the insulation and the ratio of the 'heated perimeter', divided by the sectional area of the section. It can be seen that the ratio, 'A/HP', which has the dimensions of thickness, is equivalent to the thickness of the metal in the test.

2. Experimental

The measurements were carried out using a constant heat flux test with a calibrated propane burner (Bulfinch), as shown in Figure 1, as reported elsewhere[7]. The hot face temperature in the test was controlled a constant value. 150 mm square test samples, were used, comprising the fire protection material bonded to a 10 mm thick steel substrate protected around heat flux around the edges by Kaowool ceramic fibre insulation. In the present study the rear face of the substrate was open to the air. However, it should be noted that a fully insulated rear face could also be treated by the model.

The steel plate temperature was measured during the test by a thermocouple placed in a 5 mm deep hole in the centre. The temperature of the steel enabled the heat flux through the fire protection material to be found, thus employing the plate, effectively, as a heat flux meter. A burner-to-sample distance of 350 mm was used throughout the tests. The burner gas pressure was adjusted to ensure that a temperature, T_{fire}, of 900 ºC, as measured with

2

a k-type thermocouple, was maintained at a point 10 mm in front of the test sample. The heat flux at the sample surface was measured to be 113 kW/m^2.

The three materials employed in the tests and modelling, which were bonded to 10mm thick steel substrates were:

   (i)   Kaowool fibrous insulation, 12.5mm and 25mm thick.
   (ii)   Phenolic/ceramic prill insulation, 12.5mm and 25mm thick.
   (iii)   Proprietary epoxy-based PFP, 16mm and 32mm thick.

Figure 1: Propane burner test set-up for measurements on composite PFP.

3. Theory

It will first be assumed that, following the moment of initial fire exposure, the front face temperature, T_1, of the fire protection material is constant. The heat flux, q, into the protection layer is given by the Stefan-Boltzmann relationship:

$$q = \sigma e \left(T_{Fire}^4 - T_1^4 \right)$$
[1]

where σ is the Stefan-Boltzmann constant (Wm^{-2}K^{-4}), e is the absorptivity of the protection surface, T_{Fire} (K) is the fire temperature and T_1 (K) is the surface temperature.

3.1 Model 1

There is a solution of Laplace's equation which describes to the transient situation[8-11]. The model has not been used widely in the area of heat flow, but its diffusion analogue is often employed in modelling gas permeation through polymer membranes.

The model takes account of the unsteady-state heat transfer and initial non-linear temperature profile through the PFP layer, but it assumes a constant temperature difference across the protection layer, thus neglecting the effect of the temperature rise in the metal substrate. This is a reasonable assumption as long as the temperature rise in the metal is small, compared with $T_1 - T_0$, but leads to errors when the substrate temperature rises significantly, compared to the hot face temperature.

According to this model the accumulated heat flow per unit area, $Q(t)$, from the beginning of fire exposure, through the protection material is given by

$$Q(t) = k(T_1 - T_0)\left[\frac{t}{X} - \frac{X}{a}\left(\frac{1}{6} + \frac{2}{p^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\exp\left(-\frac{n^2 p^2 a t}{X^2}\right)\right)\right]$$ [2]

where $T_0 =$ initial uniform temperature of the PFP and substrate,

$T_1 =$ hot face temperature of the PFP, and

$X =$ the PFP thickness.

This model can be seen to involve only the thermal diffusivity, as opposed to the conductivity, of the PFP. Since the substrate possesses a metallic level of thermal conductivity, temperature differences through its thickness will be neglected, so the 'lumped parameter' model will be taken to apply. The temperature rise in the substrate can thus be related to $Q(t)$ by

$$Q(t) = r_m C_{Pm} b (T - T_0)$$

so the metal temperature is given by

$$T = T_0 + \frac{k(T_1 - T_0)}{r_m C_{Pm} b}\left[\frac{t}{X} - \frac{X}{a}\left(\frac{1}{6} + \frac{2}{p^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\exp\left(-\frac{n^2 p^2 a t}{X^2}\right)\right)\right]$$ [3]

Five terms are generally sufficient to achieve convergence of the series of exponential terms. At short times it describes the induction period well.

For the PFP the main property influencing the induction time is the initial thermal diffusivity, the 'effective' value of which is given by

$$\alpha = \frac{X^2}{6 t_0}$$ [4]

$$t_0 = \frac{X^2}{6 a}$$ [5]

At longer times, after the sum of the exponential terms in Equation (3) approaches zero a linear relationship between substrate temperature and time is predicted. In this region the PFP, acts as a simple resistance to heat transfer, without heat accumulation, so

4

$$Q(t) = k(T_1 - T_0)\left(\frac{t}{X} - \frac{X}{6\alpha}\right) = \frac{k(T_1 - T_0)(t - t_0)}{X} \qquad [6]$$

In principle, the long term thermal conductivity of the PFP can be found from the slope of the linear part of the curve. As mentioned, this relationship, in practice, can be expected to become non-linear, as the substrate warms up, which is why a second model is needed for this region.

3.2 Model 2

This model neglects heat accumulation in the PFP, as well as other exo- and endothermic effect. It considers only PFP's resistance to heat transfer into the metal. This condition is probably applicable at later stages in the fire exposure, after the initial transient period, which is ignored here.

Account can be taken of convective heat losses from the rear face of the substrate, which have a significant influence. So, a heat balance can be made. The heat conducted through the PFP corresponds to the enthalpy change of the substrate, plus the rear face convective losses, so

$$\frac{(T_1 - T)k}{X} = \frac{dT}{dt}\rho_m C_{Pm} b + (T - T_o)h \qquad [7]$$

Re-arranging gives

$$\frac{dT}{T_1 - T}\frac{k}{X} = \frac{dT}{dt}\rho_m C_{Pm} b + (T - T_o)h \qquad [8]$$

which can be re-arranged to form the differential equation:

$$dT \left/ \left(-T + \frac{\dfrac{T_1 k}{X} + T_0 h}{\dfrac{k}{X} + h}\right) = \left(\frac{\dfrac{k}{X} + h}{\rho_m C_{Pm} b}\right) dt \right. \qquad [9]$$

Integrating this and applying the boundary condition that the temperature is T_0 at $t = t_0$, gives the following exponential relationship

$$T = \frac{\dfrac{T_1 k}{X} + T_0 h}{\dfrac{k}{X} + h} + \left(T_0 - \frac{\dfrac{T_1 k}{X} + T_0 h}{\dfrac{k}{X} + h}\right)\exp\left(\frac{-\left(\dfrac{k}{X} + h\right)(t - t_0)}{\rho_m C_{Pm} b}\right) \qquad [10]$$

If the rear face heat loss is neglected, this simplifies to

5

$$T = T_1 + (T_0 - T_1) \exp\left(\frac{-k(t - t_0)}{r_m C_{Pm} b X}\right)$$

[11]

A reasonable approximation can be achieved by simply equating t_o in Equation (10) by the value given by Model 2 in Equation (5). However the curves for the two models do not co-incide exactly at the crossover point. A better procedure is simply to adjust the thermal diffusivity value in Equation (5) by eye so that the two curves co-incide at the crossover point, as shown in Figure 2.

The procedure proposed for characterising PFP behaviour, therefore involves fitting the experimental results to Equation (10) in the region beyond the induction period. This can be done by manipulating three variables: the induction time, the thermal conductivity of the char and the rear face heat transfer coefficient.
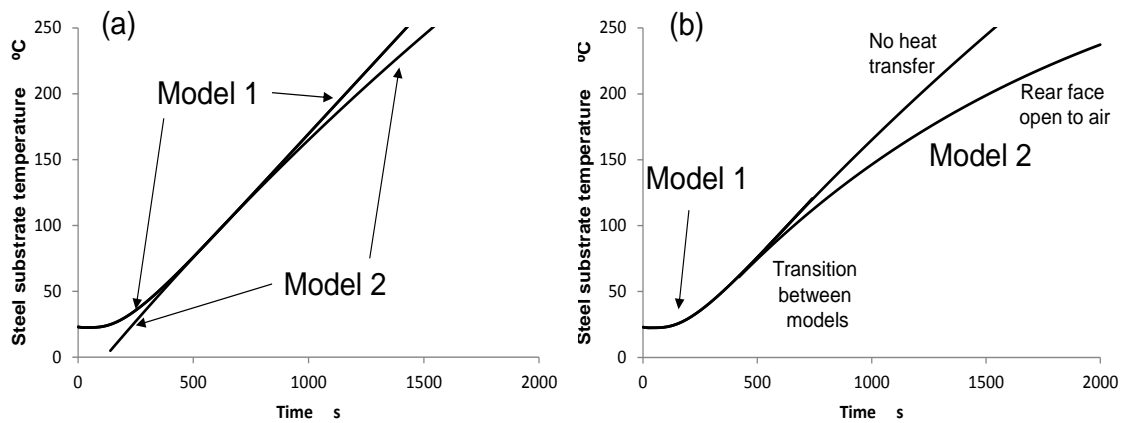
Figure 2. (a) Model 1 and Model 2 (with a displaced time axis. (b) Combined model, with prediction for the fully insulated case and the rear face open to air.

It is interesting to note that the long term behaviour under heat flux is significantly affected by the rear face heat transfer coefficient. In the results reported here the steel substrate rear face was open to the atmosphere and the HTC was adjusted to ensure the model fitted the data. It was since been found beneficial to carry out test with an insulated rear face, in which case heat losses can be neglected.

4. Results and discussion

Figures 3-5 show the results obtained for the substrate temperature measurements on the Kaowool, the phenolic/prills and the intumescent system. It can be seen that the model, essentially Model 2, Equation (10), is able to fit all the observed results. In the case of the Kaowool PFP, Figure 3, the fit is achieved using the same thermal constants for both the thin and thick PFP. In the case of the thinner PFP the HTC needed to fit the results was higher for the thinner sample, but this is to be expected as the HTC for convective heat transfer does increase. This means that, within the range of thickness covered by the tests, the heat transmission can be modelled using the same values for thermal conductivity and diffusivity.

For the phenolic prills a similar result was seen, again showing that the PFP can potentially be characterised by Equation [10] over a wide range of thickness. It is

6

interesting to note that neither the Kaowool nor the Phenolic samples expanded significantly during the fire exposure.

In the case of the intumescent material it was also possible to fit the response curves but a significantly lower value of thermal conductivity was needed for the thicker sample. This implies that the effective conductivity may be a function of the initial material thickness and how the intumescing process proceeds in the thin and thick cases. It would still be possible to use Equation [10] to model the behaviour, but the value assumed for thermal conductivity would needed to be regarded as a function of initial thickness. This is perhaps not so surprising, given that the Intumescent samples expand by a factor of about 15 prior to reaching the 'steady state' conducting condition.
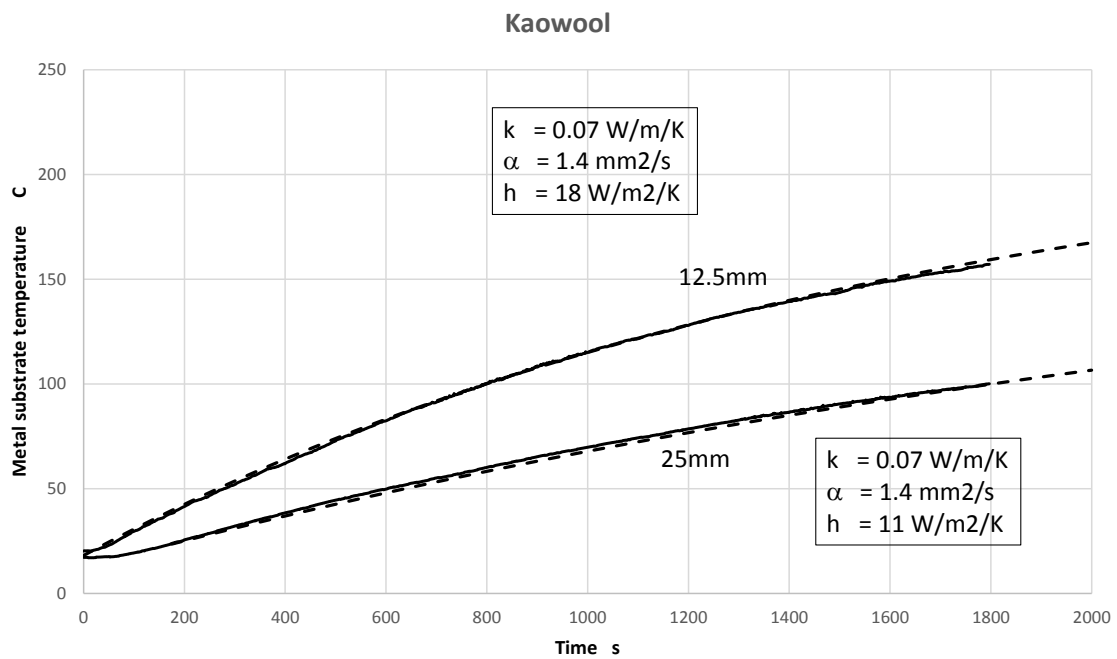
Figure 3. Measured and modelled 10mm steel substrate temperature vs. time for Kaowool PFP with 900^0 C hot face temperature and the rear face open to air. PFP thickness was 12.5mm (upper curve) and 25mm (lower curve).

Phenolic-prill composite
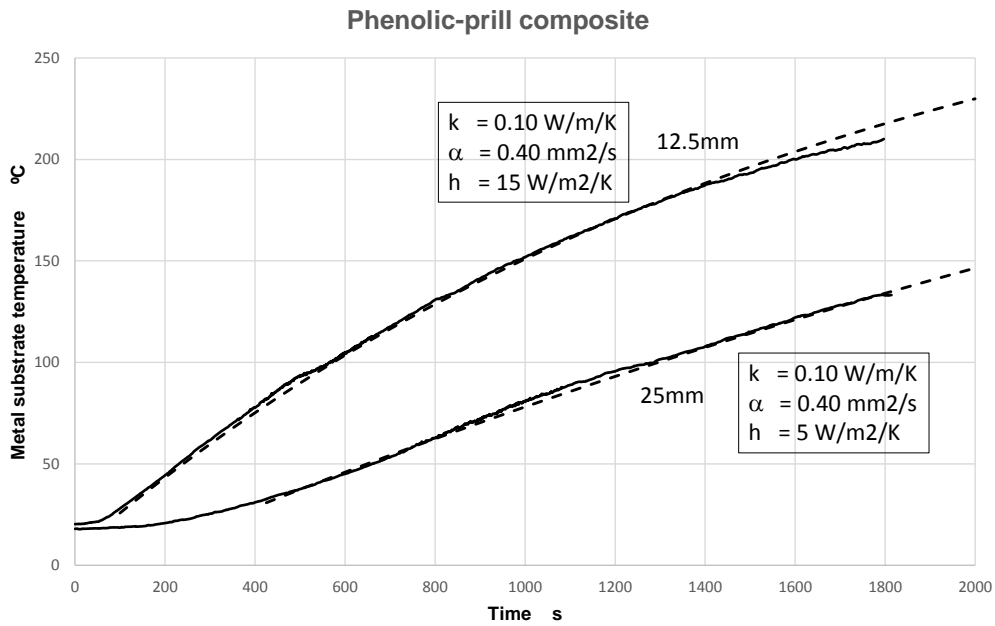
Figure 4. Measured and modelled 10mm steel substrate temperature vs. time for phenolic/prills PFP with 900⁰ C hot face temperature and the rear face open to air. PFP thickness was 12.5mm (upper curve) and 25mm (lower curve).
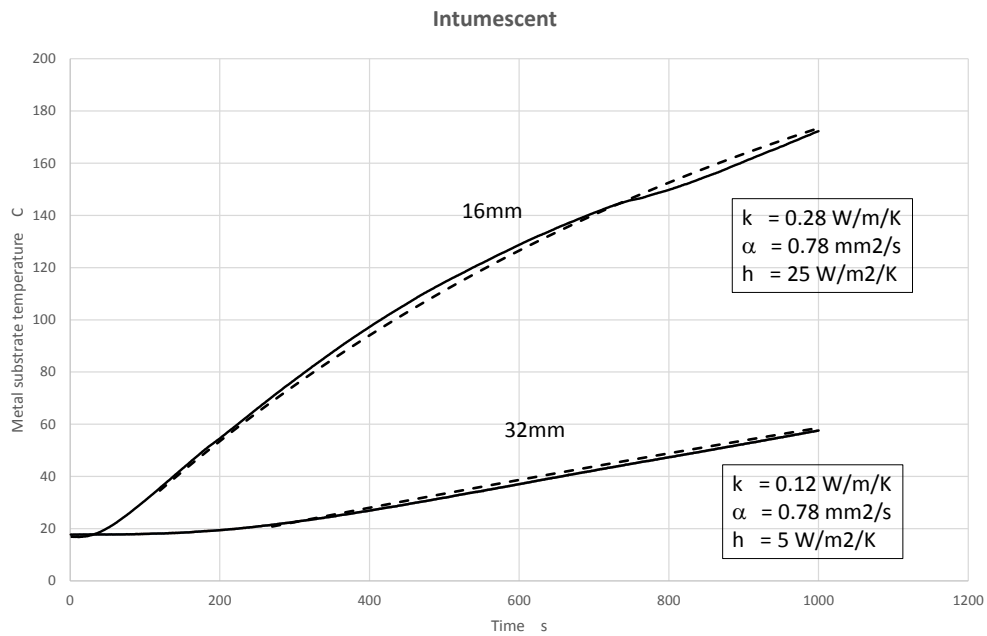
Intumescent

Figure 5. Measured and modelled 10mm steel substrate temperature vs. time for an intumescent PFP with 900⁰ C hot face temperature and the rear face open to air. PFP thickness was 16mm (upper curve) and 32mm (lower curve).

8

5. Conclusions

The results reported here show that the simplified 'lumped parameter' model of Equation [10] can be used as the basis for modelling and design of PFP of all types. However, in the case of intumescing materials, it is necessary to employ thermal properties that depend on the initial thickness of the PFP.

6. References

1. A.G. Gibson, '*Composite materials in the offshore industry*', Chapter 6.23 of *Comprehensive Composite Materials*, Editors A. Kelly and C. Zweben, Elsevier, 2000.

2. H.J. Vandersall. *Intumescent coating systems: their development and chemistry*. J. Fire and Flamm., 2 1971 97-140.

3. G. Camino, L. Costa, L. Trossarelli, *Study of the mechanics of intumescence in fire retardant polymers: Part 1 Thermal degradation of APP-PE mixtures*. Polym Deg Stab. 6 (1984) 243-252.

4. A.P. Mouritz, S. Feih, E. Kandare, Z. Mathys, , A.G.Gibson, P.E. DesJardin, S.W. Case, B.Y. Lattimer,. *Review of fire structural modelling of polymer composites*. (2009) Composites A, 40 12 1800-1814.

5. A.P. Mouritz, S. Feih, E. Kandare, A.G.Gibson, *Thermal-mechanical modelling of laminates with fire protective coating*. Composites B, 48 (2013) 68-7811.

6. E. Kandare, G.J. Griffin, S. Feih, A.G.Gibson, B.Y. Lattimer, A.P. Mouritz. *Fire structural modelling of fibre-polymer laminates protected with an intumescent coating*. Composites A, 43 (2012) 793-802.

7. P. Tranchard, F. Samyn, S. Duquesne, M. Thomas, B. Estebe, M-L Montes, S. Bourbigot, *Fire behaviour of carbon fibre epoxy composites for aircraft: novel test bench and experimental study*, J. of fire Sciences, (2014) 33(3) pp247-266.

8. J. Crank and G.S. Park (Eds) *Diffusion in Polymers*, Academic Press, London and New York, 1968.

9. B. Flaconnèche, M-H. Klopffer and J. Martin, *Oil & Gas Science and Technology*, 2001, **56**, 261-278

10. H S Carslaw and J C Jaeger, *Conduction of Heat in Solids*, Oxford University Press, 2nd Edition, 1959.

11. J. Crank, *The Mathematics of Diffusion*, Clarendon Press, Oxford, 2nd Edition. 1975.