Key Points For Large Structures Fire Tests Modeling

A. C. Goupil, J. C. Craveur, P. Barabinot

***Abstract*—Structural behavior of composites panels when exposed to fire is a critical issue for civil engineering, aeronautics and naval industries. This field has been studied for a long time, especially about the thermal degradation of resins. A lot of work has also been done on the mechanical response of composites, firstly about post-fire properties and then about analytical methods. Finite element analysis is sometimes used to validate assumptions through the comparison of experimental curves, typically time-to-failure or in best cases time-deflexion curves, but not in the aim of describing sequentially the steps of the collapse of a structure in fire.**

The goal of this paper is, therefore, to explain precisely the pitfalls one can encounter when modeling thermo-mechanical responses of such structures. They are of different types: material properties but also conditions of experiment.

***Index Terms*—Composite, Fire, Thermo mechanical**

I. INTRODUCTION

THE International Maritime Organisation imposes that all ships whose tonnage is more than 500 must respect the SOLAS (Safety Of Life At Sea) regulation. First, steel and other non-combustible materials were allowed on board but composite materials can now be tolerated in some particular cases. Like the prescriptive designs, the alternative designs must withstand both thermal and mechanical loads imposed during normalized tests. For prescriptive designs, each bulkhead and each part of the deck is more or less protected against fire according to the regulation and the fire risk associated to each room on the ship. As steel is a good thermal conductor, fire insulation is required to prevent heat increase in the neighboring rooms. This insulation, quite thick, fills a part of the room volume. And in addition to this, the installation of the covering, which is rather complex, is long and expensive. Sandwich panels, on the contrary, have a low conductivity so they are easy to install especially because they do not need any stiffener. They are also lighter than metallic panels and for military application. The fact that their radar signature is reduced is an advantage. However, they degrade when exposed to high temperatures. Several issues ensue from this. First, they emit toxic fumes and soot that can suffocate people and prevent them from escaping. Then they lose mechanical properties at quite low temperature (about 200°C). The critical stake is to build the lightest panels with the longest time-to-failure. As a consequence, two strategies are conceivable. The first one is to cover the composite panel with an insulation blanket as is done with metal panels. But the gain is minimal compared to metal. The second option is to study and understand each step of the decomposition in the thermal response as well as in the mechanical response. Thus, the design of the panel without fire protection, or with a thin fire protection, could fulfill the specifications of the ship manufacturer. The objective of this paper is to contribute to this last way of thinking by methodically explaining what is needed, what is available and the safety measures necessary. All of the questions will not necessarily be answered but a marked out path will be drawn up. The speech progress will follow a pyramidal structure beginning from the top (the naval panel) to the base (material) (Fig. 1.). The arrows stand for the numerical readjustments.

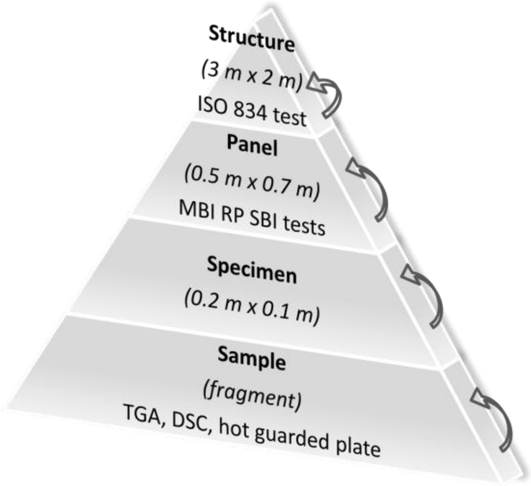

Fig. 1. Progress of experimental tests

First, the structure and the validation tests will be presented, then the thermo-mechanical model will be explained. These lines will lead to the analytical expressions implemented in these models and then to the material properties. This last point is the critical one because an error at the base could be amplified when the complexity increases.

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II. STRUCTURE

A. *Panel use and constitution*

Panels are used in the naval industry for bulkheads and decks. For fire tests achieved according to the FTP code, the specimens have given dimensions. Bulkhead sizes are 2.44 m x 2,50 m and deck sizes are 3.04 m x 2,44 m. Both types of panels are made of sandwich composites whose core is made of balsawood and skins made of glass fiber / vinyl ester. The choice of these materials is a compromise between cost and efficiency. Phenolic resins have a low heat release rate and they give off fumes, they are not easy to manufacture and are expensive. Vinyl ester resins release a little more heat but are cheaper. Balsawood is very light and rot proof. The challenge is then to be able to model the behavior of typical sandwiches subjected to a ISO 834 fire or an hydrocarbon fire, and obtain results close enough to experimental tests despite the uncertainties. This is even more the case for large structures compared to specimens with dimensions of 15 cm x 15 cm. The volume of material induces more or less a disparity in properties. This phenomenon is well known by people studying delamination and especially initiation through coupling with ply damage [1]. Moreover, if the temperature is assumed to be uniform on the exposed face of small specimens, this assumption cannot be made for large panels.

B. *Certification tests*

To be certified and used in ships, panels must pass the standard tests. These are fully described in regulation codes. The devices used in ship building for IMO approval are Medium Burning Item, Radiant Panel Test, Single Burning Item and ISO 834 test (Fig. 1). The latter test consists of closing a furnace with the panel tested. Of course, the missing wall varies in the case of decks (Fig. 2) or bulkheads (Fig. 3).

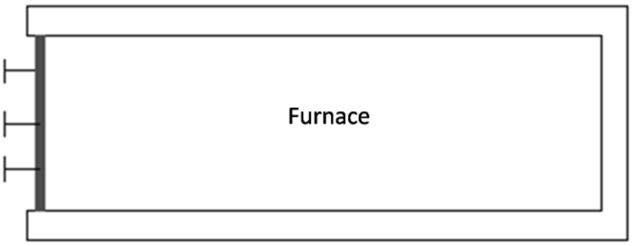

Fig. 2. Furnace set-up for bulkheads

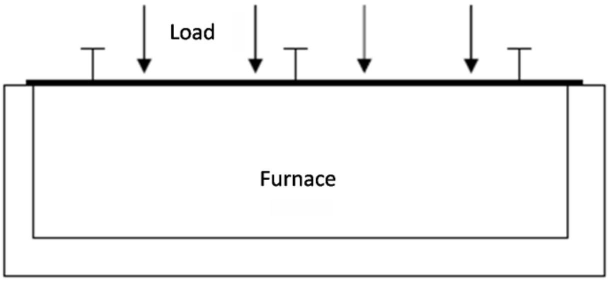

Fig. 3. Furnace set-up for decks

In the furnace, burners provide heat, the furnace temperature and its homogeneity are retro-controlled measuring the gas temperature which must respect the set point described by an analytical expression (Table I). The temperature of the air on the back side is assumed to be constant. The heat exchange between the gas and the structure is said to be the product of both convection and radiation, the emissivity and convection coefficients are assumed to be uniform and constant (Table I).

TABLE I
UNITS BOUNDARY CONDITIONS FOR ISO 834 TEST [2]

Side	Hot side	Cold side
h_c ($W.m^{-2}.K^{-1}$)	25	5
ε_r	0.8 to 1	0.7
T (°C)	T_0+345log (8t+1)	20°C

The success of these tests is estimated through the measurement of temperatures in several points of the back face imposed by the regulation. The criterion includes the maximum and the average temperature monitored. In addition, the panel must not let the flame go through before a given time with respect to the regulation.

III. NUMERICAL MODELLING

At each step of the test pyramid, numerical modeling is used to validate information and properties extracted. Our purpose is to model a large structure and to predict the behavior of a similar one. A problem we will face is that properties obtained from samples may not be useful for large scale structures.

Several ways can be used to model a thermo-mechanical problem and the most convenient is to separate the thermal analysis from the mechanical one. First, the thermal analysis is done, and at each step time of the mechanical response, the temperatures calculated are then applied to the nodes of the mechanical mesh for the computations. This kind of analysis is called “decoupled thermo-mechanical analysis”. When the flux begins to heat the panels, it can be observed that the exposed skin peels off. With sequential chaining, the convection and radiation of pyrolysis gases between the skin and balsa core are not taken into account in the thermal analysis. This can result in underestimation of the temperature. The stake is then to measure the improvement of a fully thermo-mechanical coupled model and the time-cost it implies. In the case of FTP code fire tests, the decoupling is supposed to be valid and is generally used for the simulations.

The materials that we are studying have a low conductivity, and because of this there is a large gradient of temperature along the thickness. Bricks elements are therefore used in thermal analysis. Panels have a quite large slenderness ratio but the axial stress along the length of the panels does not vary as a linear function across the thickness. Thus, volume elements are also used in mechanical analysis. Thermal and mechanical properties will, indeed, be different on the “hot skin” and on the “cold skin” because of the thermal dependency. Depending on the finite element software, the thermal mesh and the mechanical mech can be different, but we choose to have identical meshes to avoid time and spatial interpolation.

IV. ANALYTICAL MODELS

A. *Thermal analysis*

Regardless of the materials, when subjected to increasingly high temperatures on the hot face, the heat transfer inside the panel is due to conduction. For polymer resin composites, depending on the temperature elevation, the energy provided is high enough to degrade the polymers by thermolysis and sometimes oxidation. In case of vinyl ester resin, the reaction is endothermic: energy is absorbed by the reaction, the temperature does not increase. Products of thermolysis are char and gases. These gases go through the char layer and cool the specimen down by convection. The process is completed by the inflammation of gases when they find oxygen at the free surface, which is an exothermic phenomenon. If temperatures keep on rising, chemical reactions can occur between char and silica from fibers. Henderson proposes a model which takes into account all those phenomena [3], [4]. In the following equations, ρ is the density, h the enthalpy, λ the conductivity, c_p the specific heat, Q the heat of decomposition, d the gas mass flow, T the temperature, x the position and t the time. The following subscripts: *0*, *c*, *g* and *r* refer to virgin material, char material, gases and resin. All these quantities are collected in Table II.

$$\begin{aligned} &d(\rho h)/dt = \partial/\partial x\left(\lambda\,\partial T/\partial x\right) - \partial/\partial x\left(d_g h_g\right) \\ &-Q\,\partial\rho_r/\partial t \end{aligned} \tag{1}$$

The first term of the right member in the above equation represents conduction, the second one, the cooling convection flow of pyrolysis gases and the third one corresponds to the heat absorbed during resin degradation. Because glass fibers are inert, all the of mass loss is due to resin loss, then:

$$\partial\rho_r/\partial t = \partial\rho/\partial t \tag{2}$$

Using the following definition of the specific heat:

$$c_p = \partial h/\partial T \tag{3}$$

the previous expression becomes the following one.

$$\begin{aligned} &\rho c_p\,\partial T/\partial t = \partial/\partial x\left(\lambda\,\partial T/\partial x\right) - d_g c_{pg}\,\partial T/\partial t \\ &-(Q + h - h_g)\,\partial\rho/\partial t \end{aligned} \tag{4}$$

c_p, c_{pg}, h, h_g and Q are properties of the material, whose evolution in function of the temperature can be measured. The density change of the material ρ and its change rate $\dot{\rho}$ are due to the resin degradation. This reaction follows an Arrhenius type kinetic rate equation. The gas flow d_g is directly linked to the mass loss through the conservation of mass rule. A, E_a and n are Arrhenius parameters and are referred to as prefactor, activation energy and order of reaction. R is the perfect gas constant.

$$\partial\rho/\partial t = -A\left(\left(\rho - \rho_c\right)^n/\left(\rho_0 - \rho_c\right)\right)\exp\left(-E_a/RT\right) \tag{5}$$

$$\partial\rho/\partial t = -\partial d_g/\partial x \tag{6}$$

$$d_g = -\int_x^l (\partial\rho/\partial t)\,dx \tag{7}$$

The model is thus a set of three coupled, nonlinear, spatio-temporal equations which must be solved simultaneously. This involves a lot of iterations to solve the process. Supposing all of the data required for simulations were documented, the computation time and computer resources would be sizeable, especially when the analysis concerns large structures such a bulkhead or a deck, for which the model size can be over 100000 degrees of freedom.

Lattimer and Ouellette [5] proposed to simplify the set in one equation thanks to the quantity called “apparent capacity” which collects the effects of the specific heat, the heat absorbed by pyrolysis and the loss of mass. The effects of gases (convective cooling and capacitive effect) are neglected.

$$\rho_o c_{app}\,\partial T/\partial t = \partial/\partial x\left(\lambda\,\partial T/\partial t\right) \tag{8}$$

Where

$$\rho_o c_{app} = \left\lfloor \rho c_p + \left(Q_{decomp} + h\right)\partial\rho/\partial T \right\rfloor \tag{9}$$

The advantage is to decrease the calculation cost and reduce the number of parameters needed for the analysis. However, it has not been proven that gases can be neglected. Looyeh studied the impact of each term of the equation and showed that gases contributed significantly to the structure cooling [6]. Even if the equation obtained using the apparent capacity is easier to solve, material parameters are always needed.

B. *Mechanical analysis*

The mechanical model is in most cases a classic static one with temperature dependent material properties. The contribution of temperature is double: changes in the mechanical properties such as Young’s modulus *E*, yield stress, and differential dilatations due to the gradient of temperature inside the structure. The strain ε is then given by the formula indicated below where: σ is the stress and α, the dilatation coefficient.

$$\varepsilon = \sigma/E + \alpha\Delta T \tag{10}$$

Thermal gradient will induce bending, and damage between plies or between the skins and the core. Several types of structure failure can occur and a specific criterion is associated with each mode. Among them are buckling, skin wrinkling, plastic kinking of the skin and shear failure of the core. All those modes have been observed for small samples (typically 15 cm x 6 cm) depending on their thickness, boundary conditions and loading. However, due to the size and slenderness of ship panels, some of those effects will not be encountered.

V. V-MATERIAL PROPERTIES

A. *Thermal*

Three temperature dependent quantities (conductivity, specific heat and density) must be known for four materials (virgin, char, pyrolysis gases and naked fibers) for the simulation. Anisotropy of the materials is not taken into account for the ISO 834 fire test as the heat flow is 1D, and the flux applied to the hot face is supposed to be uniform. But for other tests, this assumption is no longer correct and more data is needed

1) *Conductivity*

Laboratories specialized in thermal properties measurements use various techniques among which is the guarded hot plates. Precise values (1% of uncertainty) are obtained and it is well suited for materials with low conductivities that are less than 2 W.m^{-1}.K^{-1}. Moreover the size of the sample can be 60 cm x 60 cm. However, contact resistance can affect the measurements. Because of the panel size, such precision is not useful. That is why some laboratories have developed other devices. One of them which is called Thermal Decomposition Apparatus (TDA), is a kind of furnace in which fluxes are controlled and the temperature is measured at the center of the sample (0.10 m x 0.10 m) [5]. Constant heat fluxes and ramping heat flux tests are applied. TDA is used for virgin material, char and naked fibers. Gas effects during decomposition are not useful because they have already been taken into account in the effective property due to the set-up chosen. One drawback of this technique is that only the panel transverse conductivity can be measured. Glass fiber / vinyl ester resin is a composite material. The mixing law can sometimes be used to determine composite properties from fiber and resin properties. However, it is well known that the mixing law is not adapted for in-plane properties. Some authors have decided to get around the difficulties of determining temperature and mass dependent properties by using a virtual testing tool based on an inverse solution [7]. The input data consists of effective properties of both fiber and matrix coming from uni-directional composite testing along the fiber, fiber fraction, and weaving information. However, in–plane and transverse conductivities are given only at room temperature.

2) *Specific heat*

Usually Differential Scanning Calorimetry (DSC) is used to determine the specific heat. This technique gives accurate results but can only be done with samples of 15-20 mg. For composite materials, this mass is below the mass of the representative volume. This means that the properties at that scale can be different from the properties at the structural scale. Moreover, the mass is not measured during the test while the heat needed to raise the temperature is linked to the product of both the mass and the specific heat. Lattimer and Ouellette found in [5] that the specific heat of a coupon sample tested in TDA was 15 % different from the one obtained with DSC. The apparent capacity interest (eq 8) is to reduce the number of equations and the number of properties needed for the simulation. Lattimer and Ouellette measured this property for two heating rates and three specimens' sizes. Then they used these three values to predict temperature across a composite plate.

3) *Mass loss*

Mass loss is the most important information because it is linked to specific heat and it is also used in computing the conductivity value during decomposition. During pyrolysis, the material concerned is a mixture of virgin and char. That is why the mixing law is used to evaluate conductivity:

$$\lambda = F\lambda_0 + (1-F)\lambda_c \tag{11}$$

Where

$$F = (\rho - \rho_c)/(\rho_0 - \rho_c) \tag{12}$$

F (decomposition factor) is usually obtained by Thermal Gravimetric Analysis (TGA) where the sample mass (15-25 mg) is measured during the heat increase. Some uncertainties remain. The sample size is too small with regards to large structure size and the scale effect can affect the data for simulation. The temperature measured is not the sample one but the gas one which is different. The main assumption of the TGA is that the sample is so thin that the temperature is uniform in the specimen. Even for thin samples, it is not uniform according to the heating rate. This is a key point given that a *F* factor value corresponds to a given temperature. Marquis warns that high heating rates (>10°C/min) can lead to inaccurate results. He explains that the thermal and gaseous diffusivity can be altered and the thermo-chemical equilibrium may change [8]. It must be kept in mind that for an ISO 834 fire test, the heating rate is about 100°C/min during the first five minutes of fire exposure. Literature provides lots of parameters for Arrhenius law. But often a set of parameters is given for the whole range of heating rate. Lattimer and Ouellette have supplied Arrhenius parameters for several heating rates and an average set called "best fit". From this information, the evolution of *F* versus temperature is calculated. In case of powders, “best fit” parameters and specific sets give close results. In case of fragments, a difference less than 20°C is observed for the temperature marking the beginning of the mass loss. This was mainly noticed for low (2°C/min) and high (32°C/min) heating rates. This means that the average parameters should be used with caution.

4) *Heat of decomposition*

Little data is available about heat of decomposition. Agurwal and Lattimer in [9] have made improvements to the classical way of calculating decomposition. Previously, it was done by substituting specific capacity from apparent capacity. It was noticed that measured values vary a lot depending on the sample size. The method proposes to calculate the same quantity. However, in order for the quantity not to be dependent on the fiber fraction nor on the initial mass or heating rates, it would be necessary to divide this quantity by volatile mass loss. However, in most of the available documents, techniques used to obtain the heat of decomposition values are not explained.

5) *Balsawood*

All of the problems encountered with composites explained in the previous paragraphs are the same for balsawood. Uncertainties concerning the properties are even more important for this living material. There are discrepancies in the properties between two trees which have come from the same place and even between several parts of the same tree. Little data is available because experimental results are not reproducible for this reason. A question remains about the steps of decomposition. In [10], Lattimer presents a multistep decomposition process that implies several Arrhenius laws, however, Feih in [11] uses a one-step degradation model. In [8], Marquis shows the complexity of wood thermo-chemistry. The aim is to estimate the loss of information induced by simplification of the pyrolysis reaction. A special issue with balsawood is its moisture content. The water and then the vapor migration will of course affect conductivity and capacity but another issue is also the mass loss.

6) *Thermal boundary conditions*

In all tests, structures exchange heat with surrounding gases by convection and radiation. The boundary conditions are seldom detailed. When the convection and radiation coefficients, h_c and ε_r, are provided, no estimation of the gases temperature is given. If it is easy to guess the temperature on the cold side by using a correlation from which the convection coefficient can be estimated. It is, however, more difficult to follow this same procedure when dealing with the hot side. This is an issue mainly for radiant panel tests and medium burning item tests because the flux given in the data is supposed to be the imposed flux and not the net flux. Moreover, h_c is expected to depend on the physical conditions (temperature, size of the panel and velocity of the gas flow). Jowsey in [12] showed that the longer the panel is the less influence it has on the value of h. There were similar results for high temperatures.

TABLE II
UNITS AND SYMBOL OF QUANTITIES

Symbol	Quantity	Unit
ρ	density	kg/m^3
h	enthalpy	J/kg
c_p	specific capacity	J/kg.K
C_{app}	apparent capacity	J/kg.K
Q	heat of decomposition	kJ/kg
λ	conductivity	W/m.K
d	gas mass flow rate	
T	temperature	K
x	position	m
t	time	s
A	prefactor	s^{-1}
$\mathrm{E_a}$	activation energy	J/mol
n	reaction order	
R	Perfect gas constant	8.31 J/mol.K
ε	strain	MPa
σ	stress	
E	Young modulus	MPa
α	Dilatation coefficient	°C^{-1}
T_k	Half value temperature	K
k		
P_r	Initial value of property	MPa
P_i	Residual value of property	MPa
h_c	Convection coefficient	W.m^2.K^{-1}
ε_r	Radiation coefficient	

Subscript	Meaning
0	Virgin material
c	Char material
g	gas
r	resin

However the velocity seems to have a larger influence on the h value even for flat plates in laminar conditions (from 4 W/m².K at 2 m/s^{-1} to 12 W/m².K at 10 m/s^{-1}). For natural fires, all the dependences of h_c will have an influence and some CFD specific tools could assist in obtaining the coefficient value.

Another part of boundary conditions is often missing: the effect of the combustion of pyrolysis gases when they reach the free surface on hot side. Looyeh [6] gives some formulas to estimate the value of the flux induced by combustion but he takes into account both the combustion and the reaction between the char and the silica in the fibers assuming that the very high temperature is the cause of both phenomena. An improvement could be to take into account: the convection and radiation in the cavity formed by the peeled skin and core face. This implies a model with a strong coupling between thermal and mechanical analyses.

B. *Mechanical properties*

The evolution of mechanical properties differs from the solicitation applied to the structure. When the structure is compressed, the resin behavior is prevalent and the property (modulus or strength) decreases when the glass transition point is reached [13]. When decomposition occurs, the char mechanical properties are almost nil. To describe this behavior, several semi-empirical laws have been found, the following is the most commonly used [13]:

$$P(T)=\left(P_0+P_r\right)/2-\left(\left(P_0-P_r\right)/2\right)\times\tanh(k(T-T_k)) \quad (13)$$

T_k is the temperature reached when the property is half of the property at ambient temperature and k is a parameter which determines the slope of the curve. P_{i+} and P_r are the initial and residual values of properties. When the structure is under tension, the same model is generally used. Another essential property is the dilatation coefficient. This data is strongly dependent on the fiber volume ratio but little information is given in literature. About balsawood, the evolutions of mechanical properties with temperature are not known, nor available. The time-to-failure of a structure in a numerical model is closely linked to the criterion chosen. An accurate way to simulate the thermo mechanical behavior of the sandwich panel would be to model the delamination between plies and between the skins and the core, if it can be proven that this phenomenon leads to global failure. The finite element software takes into account the evolution of the interface properties, but the delamination mechanisms could differ from those observed at room temperature.

CONCLUSION

The goal of this paper was to point out what is required when modeling large scale structures subjected to fires, Structures are balsawood cored sandwiches with glass fiber / vinylester resin skins. When exposed to fire, according to the fire insulation, the structure can suffer from degradation, even global failure. Thermal and mechanical properties are required but those already documented are not always suited for such models. The paper focuses on the key points for the simulation of the thermo mechanical behavior of the sandwich panel and the issues the stress analysts could encounter.

REFERENCES

[1] E. Abisset, "Un mésomodèle d'endommagement des composites stratifies pour le virtual testing : Identification et validation", PhD Thesis, Ecole Normale Supérieure de Cachan, Cachan, France, 2012

[2] *FTP Code, International code for application of fire test procedures* (Resolution MSC.61(67)), International Maritime Organization, London, 1998 pp 4

[3] J. B. Henderson, T. E. Wiecek, "A mathematical model to predict the thermal response of expanding decomposing polymer composites", *Journal of composite materials*, 1987; 21 pp 373-393

[4] J. B. Henderson, T. E. Wielbelt, M. R. Tant, "A model for the thermal response of polymer composite materials with experimental verification" *Journal of composite materials* 1985; 19 pp 579-595

[5] B. Y. Lattimer, J. Ouellete, Properties of composite materials for thermal analysis involving fire, *Composite Part A 37*, 2006, pp 1068-1091

[6] M. R. Ebrahimi-Looyeh, Finite element simulation of heat flow in decomposing polymer composites, PhD Thesis, Durham University, 1999

[7] J. Lua, J. O'Brien, C. T. Key, Y. Wu, B.Y. Lattimer, "A temperature and mass dependent thermal model for fire response prediction of marine composites" *Composites: Part A 37*, 2006, pp 1024-1039

[8] D. Marquis, "Caractérisation et modélisation multi-échelle du comportement au feu d'un composite pour son utilisation en construction navale", PhD Thesis, Ecole des Mines de Nantes, Nantes, France, 2010

[9] G. Agarwal B. Y. Lattimer Method for measuring the standard heat of decomposition of materials, *Thermochimica Acta*, 2012, pp 34-47

[10] B. Y. Lattimer "Using small samples to get large-scale results", in *Proc. 4th International Conference on Composites in fire*, Newcastle, 2005, pp 117-134

[11] S. Feih, Z. Mathys, A. G. Gibson, A. P. Mouritz, Modelling compressive skin failure of sandwich composites in fire, *Journal of sandwich structures and materials*, 2008; 10 pp 217-245

[12] A. Jowsey, "Fire imposed heat fluxes for structural analysis", PhD Thesis, University of Edimburgh, Edimburgh, Scotland, 2006

[13] S. Feih, Z. Mathys, A. G. Gibson , A. P. Mouritz, "Property degradation of fiberglass composite in fire", *in Proc. 4th International Conference on Composites in fire*, Newcastle, 2005, pp 1-14