Abstract - We have analyzed the fire-mechanical behaviour of sandwich composite materials used in marine applications, as a function of the combustion time. In this light, sandwich beam samples are analyzed in terms of fire resistance kinetic and of post-combustion mechanical strength. We have shown that the materials undergo a strong degradation during 100s of fire exposure at 750°C and this degradation is linked to the top skin. Finally, a finite element modelling work is being developed to predict the thermal behavior of composite sandwich materials; this modelling must include all thermal, physical and chemical degradation processes in order to realistically report. resistance of materials in extreme temperature environment.

Key words - Fire strength; sandwich beam; durability; mechanical behaviours; moisture content

1. Introduction

Composite materials play an increasingly important role in our society. This type of material now takes over metal materials in many areas (aeronautics, naval, civil engineering...), because of their advantages in terms of lightness, stiffness and corrosion resistance but also cost and formatting. It is therefore essential to understand and evaluate the properties of composite materials in the long term (durability) in order to size and optimize the parts for particular applications. The same applies to the properties of these materials with respect to extreme external stress such as fire resistance during a fire. Sandwich composites are highly flammable, poorly heat-resistant and emit toxic materials during combustion. Also, these sandwich materials are subject to standard and we need to know their fire-mechanical behaviour before an application [1-3].

In this article, we have analysed the fire-mechanical behaviours of composite sandwich materials (polyester matrix loaded with glass fibers and bamboo core). We have analyzed, using a calorimeter cone as well as thermo-gravimetric (ATG), the temperature (i.e. fire) strength of this material to determine the kinetics of structure in fire. Fire behaviour measurements were made at 750°C and for different exposure times. This is to present to big data about the strength of sandwich materials during exposure to fire of structural and changes in the mechanical behaviours, especially in flexure. Finally, the experimental results obtained allow us to implement a numerical model predictive of the degradation undergone at high temperature by a sandwich material with a combustible core.

2. Experimental measures of fire resistance

2.1. Composite sandwich materials

Industrial materials consisting of laminated glass-polyester skins are used here, to which may be added draining polyester felts which facilitate the implementation by infusion of resin in a single operation. Because of their application in the shipbuilding industry, the samples studied consistently meet the resistance criteria imposed by EN ISO 12215-5.

2.2. Results and discussions

Effect of moisture absorption. Internal stresses induced by internal moisture content were analyzed. Moisture deformations have also been identified and a new model for the determine of diffusion coefficients has been presented [4].

Kinetics of thermal decomposition. Intra-gravity thermo-gravimetric thermo-gravimetric analyzes were performed up to 700°C to describe the thermal degradation processes of dry and water saturated bamboo. The rate of decomposition is determined simply by the mass loss of the composite as a function of time using the Arrhenius law of reaction kinetics:

$$\frac{dm}{dt} = -m_0 \left[ \frac{m-m_\infty}{m_0} \right]^n . A \cdot \exp \left( \frac{-E}{RT} \right) \tag{1}$$

With, m (t) the instantaneous mass of the material in kg; m_0 the initial mass of the material before decomposition in kg and m_\infty the final mass of the material after decomposition in kg. In this expression, we find the kinetic coefficients with A: the preexponential factor in min-1; E: the activation energy in kJ.mol-1; n: the order of the reaction and R = 8.314 J.K-1.mol-1 the constant of the perfect gases. In order to determine the kinetic coefficients of thermal degradation (coefficients A, E and n) we used the method of Kissinger which makes it possible to obtain the following results: E = 104 (2) kJ.mol-1, A = 4.1 (1) 107 s-1 and n = 1.13 (6) for a sample of dry bamboo; E = 130 (3) kJ.mol-1, A = 3.2 (4) 109 s-1 and n = 1.9 (1) for a sample of bamboo saturated with water [5]. The presence of water (saturation) in the structure influences the thermal decomposition behavior of the wood by inducing an increase in the maximum degradation temperature. This variation is explained from physico-chemical phenomena induced at high temperature.

Fire resistance measures. The experiments are carried out with a conical calorimeter (Figure 2). This allows the reproduction of the fire behavior of a material to use a radiation source. The composite sandwich samples (dimension 110 x 40 x 19 mm³) receive a heat flux emitted by a cone structured by winding an electrical resistance.
The specimen is installed at a distance of 26 mm from the heat source. The temperature of the sample, through the heat source (50 kW.m-2), is kept at 750°C during the test process. The fire temperature during a test process is between 400 and 1200°C. The ignition of the conical calorimeter is caused by a pilot fire. The combustion gases are diluted with air and entrained in a chimney. Our measurements are performed on an ATLAS Cone2 calorimeter cone present in the GeM Laboratory in the EMM team.

**Figure 2. Conical calorimeter and Specimen holder**

Three points bending measurements. The 3-point bending machine used consists of a flat base on which two supports are fixed (Figure 3). The upper part of each support consists of a 15 mm radius roller on which the test piece rests. The 3-point bending test is carried out by applying a central force to the upper surface of the test piece using a cylindrical support of radius 15 mm which moves vertically. The recorded chart of the load as a function of the deflection allows the determination of the bending rigidity (in N.mm2) as well as the shear stiffness (in N) of the sandwich structure. The bending tests are performed at a transverse force displacement speed of 10 mm.min-1.

**Figure 3. Mechanical 3-point bending tests**

As the mechanical measurements were carried out on samples obtained at different stages of thermal aging with a calorimeter cone, it is possible to plot the evolution of the force as a function of the displacement (Figure 4). As the material degrades structurally in the course of time and with increasing combustion time, it is normal to observe a decrease in maximum force as a function of the combustion time. We also notice that it is easier to distort the sample (the displacement increases). On the curve measured for a combustion time of 100 s, we clearly rewrite the typical evolution obtained for thermally aged materials. While the dry non-thermally aged sample undergoes a clear rupture, as soon as the material is thermally aged, we observe a first rupture of the test piece without the force returning to zero. There is growth and propagation of transverse micro-cracks and micro-cavities in the skins and the core, but the material retains a certain mechanical rigidity and does not break completely. The material continues to deform at almost constant force, then it breaks completely, more or less quickly depending on the sudden thermal aging.

**Figure 4. Load as a function of fire exposure sandwich beam time**

The previous measurements make it possible to plot the evolution of the maximum force reached and of the Young’s modulus as a function of the combustion time. These changes are shown in Figure 4 for the sandwich beam sample. We observe that the decrease of these two quantities is established in an exponential way. This trend has also been observed for other composite materials (Mouritz and Mathys [1]; Mouritz and Gardiner [2]; Feih et al. [3]). These curves clearly show that the material is highly degraded beyond 100s of fire exposure. We note that the mechanical strength is mainly related to the deterioration of the top skin. Indeed, for dry material the upper skin degrades completely during 100s. Then, the appearance of cracks during fire exposure further weakens the sandwich structure, thus the maximum load and the elastic modulus are enormously impacted and have low values.

**Figure 5. Mechanical property of fire exposure sandwich beam**

3. Modeling thermal degradation processes

3.1. State of context

Studies concerning the modeling of the fire strength of sandwich materials date from the years 1980-1990. The major research groups led by Henderson at the University of Rhode Island [13 - 18], Sullivan at the Marshal Space Flight Center [19 - 20], Springer at Stanford University [21 - 22], by Dimitrienko at NPO Mashinostroeniya in Moscow [23 - 24] and by Gibson at Newcastle University [25 - 27]. All developed models have
the ability to calculate the temperature distribution through a composite material exposed to fire, but they differ in their way of analyzing and taking into account phenomena. Indeed, the thermal decomposition of polymer matrix composite materials is a complex phenomenon because it combines thermal, physical and chemical processes. These processes are difficult to understand because they are not independent but have an influence on each other. This is why the modeling of the thermal degradation processes of a composite material must be examined in detail in order to understand the sequences of events that occur during exposure to high temperatures. If a mechanical stress is applied to the material being thermally degraded, the problem becomes more complex because of the interdependence of thermal-physical-chemical-mechanical processes. Coupled modeling (thermodynamic constraints/mechanical constraints) therefore remains very little developed and difficult to grasp by the current numerical models.

3.2. Methodology

As we have seen, the thermal decomposition of polymer matrix composite materials during a fire, for example, is a complex phenomenon because it combines thermal, physical and chemical processes.

Thermal processes include thermal conduction through the composite, generation or absorption of heat due to decomposition reactions of the polymer matrix, heat generation due to gas ignition, convection phenomena, production and evacuation of water vapor from the composite.

Chemical processes include the degradation of materials by "softening" of the material under the effect of heat, then the melting of materials as a function of the reaction temperature, the volatilization of the polymer matrix, the fibers and the material of the material. Soul with the production of ash.

Physical processes include the thermal expansion or contraction of materials (depending on reaction temperature and material type), an increase in the internal pressure of the composite due to the formation of various gases and the production of steam of water, the propagation of internal stresses, the delamination of the composite, the cracking of the matrix, ablation of the surface.

These processes are difficult to understand because they are not independent but have an influence on each other. When a heat flux is applied to the surface of a composite material, the first event occurring is the conduction of heat through the thickness of the material. Since most composite materials have a low coefficient of thermal conduction, a temperature gradient appears within the material.

We have just seen that taking into account a single phenomenon such as thermal conduction is complex to understand. Also, to model the thermal combustion of a composite material, it is necessary to proceed in step taking into account in a first time only the main phenomena participating in the process of degradation.

The simplest model considers only the three-dimensional thermal conduction in a composite material which is heated on one of its faces [28-32]:

$$\rho C_v \frac{dT}{dt} = \frac{d}{dx} \left[ k_x \frac{dT}{dx} \right] + \frac{d}{dy} \left[ k_y \frac{dT}{dy} \right] + \frac{d}{dz} \left[ k_z \frac{dT}{dz} \right]$$

(2)

With, \(t\) the time in seconds; \(x\) the distance across the thickness in meters; \(T(x, t)\) the temperature in Kelvin; \(\rho\) the density of the material in kg.m\(^{-3}\); \(C_p\) the mass heat of the material in J.kg\(^{-1}\).K\(^{-1}\); \(k_i\) the thermal conductivity of the material in the direction \(i (i = x, y, z)\) in W.m\(^{-1}\).K\(^{-1}\).

Equation (2) assumes that the thermal conduction of the composite does not vary with temperature in fact if the \(k_i\) are variable, this equation will take their variation into account, or as a thermal model the researchers considered that the \(k_i\) are constant in I prefer to mention the principle of the model, not the limitations of the equation. It also assumes that thermally activated processes such as resin decomposition, convective flow of volatile elements, etc., do not affect the value of the thermal conduction coefficient. Also, the validity of equation (2) is limited to low temperature cases, typically for incident heat flows less than 20 kW.m\(^{-2}\). For heat fluxes greater than 20 kW.m\(^{-2}\), the thermal model most often used to determine the temperature variation in a composite exposed to fire was developed by Henderson [13-18] whose 1D form is:

$$\rho C_v \frac{dT}{dt} = k_x \frac{dT}{dx} + \frac{dk_x}{dx} \frac{dT}{dx} + m_x C_p \frac{dT}{dt} + \frac{dp}{dt} \left( Q_i + H_c - H_g \right)$$

(3)

With, \(m_x\) the mass flow rate of gas generated during the pyrolysis of the matrix in kg.s\(^{-1}\).m\(^{-2}\); \(C_{pg}\) the specific heat of the gas generated during the pyrolysis of the matrix in J.kg\(^{-1}\).K\(^{-1}\); \(i = 1\) or 2 to denote the pyrolysis of the matrix \((i = 1)\) or the carbon / fiber reaction \((i = 2)\); \(Q1\) the pyrolytic energy of the polymeric matrix in J.kg\(^{-1}\); \(Q2\) the energy supplied / consumed by the coal / fiber reaction in J.kg\(^{-1}\); \(H_c\) the enthalpy of the composite in J.kg\(^{-1}\) and \(H_g\) the enthalpy of the gases elaborated in J.kg\(^{-1}\).

The first term of equation (3) considers the effect of thermal conduction and corresponds to part of equation (2). The second term also considers the effect of thermal conduction taking into account the variation of \(k_x\) as a function of \(T(x, t)\). The third term of equation (3) takes into account the internal thermal convection flows of gases formed during high temperature decomposition; this process produces a cooling effect of the laminate and the associated term is therefore negative. Finally, the fourth term represents the heat input or consumption resulting from the decomposition of the polymer matrix and the reactions induced between the carbon and the reinforcing fibers. In this last term, the decomposition rate of the matrix expressed by is simply determined by the loss of mass of the composite as a function of time using the Arrhenius law of reaction kinetics (equation 1) and considering a volume of fixed control.

If the volume is not constant and varies during the measurement, which is the case most of the time since the matrix decomposes and undergoes expansions/contractions due to temperature variations, a model must be considered, thermo-physical, such as that of Florio et al.
A preliminary work of modeling the temperature variation in a composite sandwich material, through the Henderson model, was established by finite elements with Abaqus software. Since the experimental measurements that we establish are carried out at moderate temperature (50 kW.m\(^{-2}\), ie 750°C), the thermal conductivity and the specific heat of the material were, as a first approximation, considered constant (equal to those of the material at room temperature) and the heat exchanged by the neglected coal / fiber reaction. During this preliminary modeling work, we were able to reproduce the results described by Feih et al. [3] concerning the spatial and temporal evolution of temperature in a sample of glass / vinyl-ester laminated composite material. The next step is to replicate this evolution for a glass / polyester-bamboo sandwich composite based on our experimental measurements. We have established a first calculation by an extremely simplified approach allowing having a qualitative variation of the temperature in the thickness of the sandwich composite as a function of the combustion time (Figure 6 and 7). This calculation does not take in addition, the thermal phenomena of conduction, convection and radiation also have a function of thermal evolution of the density parameters and the coefficient of thermal conduction. This preliminary model enabled us to verify the feasibility of the numerical approach proposed, in particular the fact of being able to modulate a parameter as a function of time and temperature, and to take into account this modulation in the variation of the other properties, thermal Firstly. This has to be thought of both for the combustible laminated glass / polyester skins and for the bamboo core which is also combustible. There is therefore a strong interaction between the thermal degradation of the skins and the soul.

4. Conclusion

We have been able to determine the thermal degradation rates for each of the constituents. We have combined these analyzes with 3-point mechanical flexure tests to identify the mechanical properties of sandwich beam samples as a function of the fire exposure time. This makes it possible to show the different stages of degradation of the sandwich structure, particularly by studying the evolution of the maximum load and the elastic modulus as a function of the sudden deformation or the fire exposure time. We have shown that the materials undergo a very strong fire degradation during the first 100s of heat exposure at 750°C and this degradation is strongly linked to the deterioration of the top skin. Finally, a finite element modeling work is being developed to predict the thermal behavior of composite sandwich structure; this modeling must include all thermal, physical and chemical degradation processes in order to realistically report resistance of materials in extreme temperature environment.

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