Mechanical behaviour of balsa wood at elevated temperature

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Abstract

From the diversity of core materials that can be used on sandwich panels, balsa wood is a strong possibility with substantial potential for civil engineering applications. Regarding the applicability of this kind of solutions in the construction industry, there is a concern about their behaviour at elevated temperatures and fire. Balsa wood as a core material works essentially in shear. In the present article, an experimental study is presented about the mechanical behavior in shear at elevated temperature of balsa wood, which includes thermophysical and mechanical tests. The tests were complemented with an analytical study and a numerical investigation. Significant reductions of the balsa wood mechanical proprieties were observed, particularly significant at temperatures of 240 °C for loading in a perpendicular direction to the fibres (RT) and up until 200 °C for loading in a parallel direction to the fibres (RL).

Keywords: Sandwich panel, balsa wood, GFRP, elevated temperatures, shear, DSC/TGA

1. Introduction

A sandwich panel is characterized by two exterior faces that are relatively thin, resistant and rigid, separated by a relatively thick core that is also lighter and less resistant and rigid. When subjected to transversal loads w.r.t. their plan, the faces are responsible for the flexural behavior of the panel and the core is responsible for the shear behavior. These panels have been gaining relevance in civil engineering with possible applications such as in building floors, bridge decks, roofs, and facades. In recent years, sandwich panels using fibre reinforced polymers (FPRs) have been developed. One of the most common FPRs used in civil engineering are the ones that use fibreglass as a reinforcing material (GFRPs, Glass Fibre Reinforced Polymers) [2].

Balsa wood, composed of hemicellulose, cellulose, and lignin, is used as a core material in sandwich panels, giving them stiffness and low weight. The more common way of producing balsa panels involves a combination of parallelepiped blocks with the fibre wood direction oriented perpendicularly to the panel plane (configuration named as end-grain). Balsa wood is mainly subjected to shear in two main planes: in the plane perpendicular to the fibres (RT) and in the plane parallel to the fibres (RL).

Inherent to the application of any material in the industry there is the concern with its behavior at an elevated temperature and fire, so that building code requirements [1] can be fulfilled. Balsa wood is susceptible to suffer detrimental effects when exposed to elevated temperatures, as shown in various studies present in the literature. These studies suggest the occurrence of thermophysical modifications and significant losses in balsa's properties, such as specific heat [3], thermal conductivity [4, 5], dehydration, decomposition [6] and compressive strength [7]. These modifications can compromise the balsa structural capacity in a possible fire or when exposed to elevated temperatures. This is why it is extremely important to complete the technical bibliography, namely in what concerns the behavior of balsa in shear for which no information is available.

In this context, several tests were performed in balsa wood, including thermophysical tests and mechanical tests at elevated temperature. For this second set of experiments, shear tests were performed because this is the most relevant behavior for the sandwich panel core. These tests had as main aim the assessment of the mass loss in the balsa wood and the resulting heat flow with increasing temperature, and the characterization of the mechanical behavior in shear as function of temperature. The shear tests were performed for temperatures between room temperature and 240º C, in the two main shear planes: RT and RL. Based on these experimental tests, different analytical models were assessed regarding their ability to reproduce the degradation of the mechanical properties of balsa in shear (shear modulus and shear strength) with temperature; these models have been used with FRP composite materials, but had not been applied to balsa wood. The main goal was to use these models to obtain degradation laws for the mechanical properties of balsa wood in shear. These curves were then used as input in numerical thermo-mechanical finite element models of the sandwich panels subjected to elevated temperature and bending. The main goal of these models was to obtain an estimate of the fire resistance of the panels, and to assess its improvement when a passive protection is used.

2. Description of the experimental programme

2.1. Materials

To perform the experimental tests, balsa wood was used, extracted from a commercial panel *Baltek® SB 50* (end grain) produced by *3A Composites* with dimensions of 1200 × 600 mm and thickness of 120 mm (without FRP laminates).

2.2. DSC/TGA tests

To perform the DSC/TGA tests three cubes with 10 mm of edge were extracted from the panel, with densities of 92,6 kg/m^3; 115,7 kg/m^3 and 104,4 kg/m^3.

From each cube, several samples with small dimensions were extracted.

For each density, DSC/TGA tests were performed on two samples. To perform these tests, a *Perkin Elmer Simultaneous Thermal Analyzer (STA) 6000* (Figure 1a) and a refrigerator/circulator of heating *Julabo F12-ED* (Figure 1b) were used. The tests were conducted in a temperature range between 30 °C and 700 °C, at a heating rate of 10 °C/minute, using nitrogen as a purge gas to perform the material pyrolysis (Figure 1c). The samples were introduced inside the calorimeter oven in an alumina crucible (Figure 1d). The time, the temperature, the samples mass and the thermal flux were measured and registered during the test and using the *Pyris™ Thermal Analysis Manager* software.

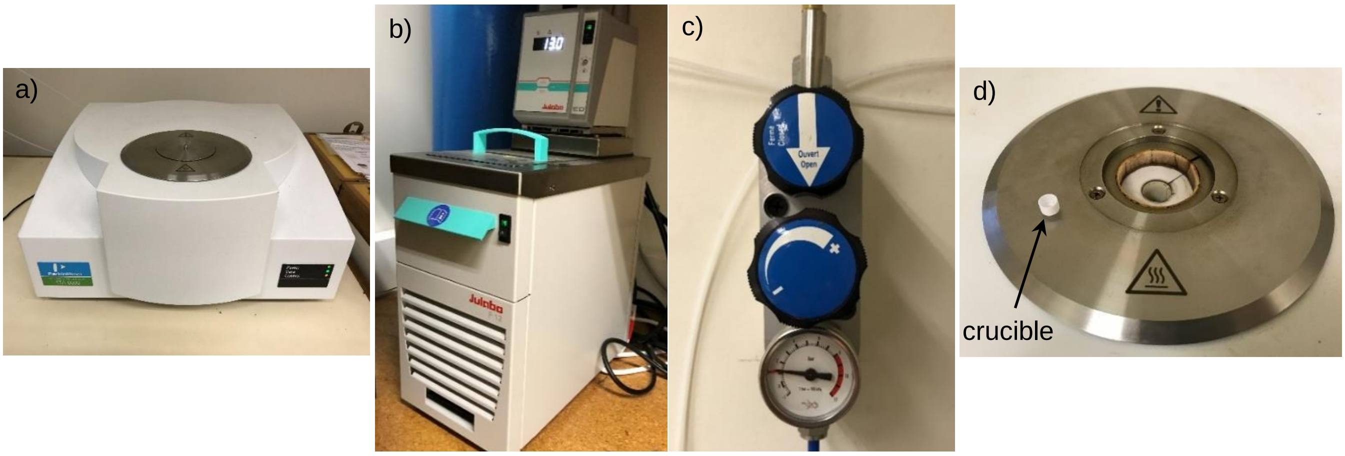

Figure 1 - DSC/TGA tests setup: a) *Perkin Elmer Simultaneous Thermal Analyzer (STA) 6000*; b) refrigerator/circulator of heating *Julabo F12-ED*; c) nitrogen valve for the purge gas; d) calorimeter oven (and its interior) with the alumina crucible

2.3. Shear tests at elevated temperature

For the determination of the balsa wood's mechanical properties in shear, tests were performed according to the *Iosipescu* method, also known as the *V-notch beam test*, described in the ASTM D5379/D5379M standard [8] for composite laminates. The samples were cut with the dimensions indicated in that standard (with thickness of 12 mm); to measure the shear deformation 8 targets were marked on the center of the sample, on 4 corners of 2 squares, one on the inside (6 mm × 6 mm) and the other on the outside (10 mm × 10 mm) (Figure 2).

Samples were extracted from two main shear planes of the balsa: RT and RL. In the RT direction, to avoid the local crushing and reduce the possibility of the sample torsion in the test device, aluminum tabs with dimensions of 20 × 25 mm^2 and thickness of 1,5 mm were applied in the extremities of the samples using an adhesive resistant to elevated temperatures (*Pattex – SL 509 solyplast*).

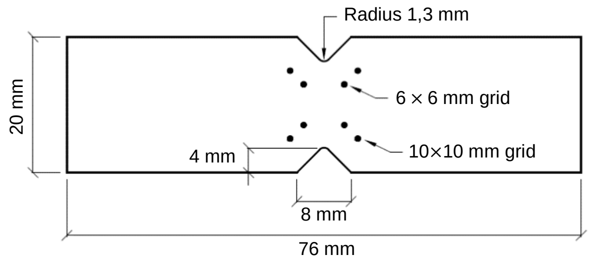

Figure 2 - Samples dimensions with the respective targets marked to measure the shear deformation

A total of 55 samples were tested, 5 for each test temperature (23 °C, 80 °C, 120 °C, 160 °C, 200 °C and 240 °C) and for both main directions, guaranteeing that the average density of each group/series was similar to that indicated on the datasheet [9]. In the RL direction, tests were not performed at the temperature of 240 °C because for this temperature the samples showed very low values of shear strength and stiffness.

The experimental procedure was equal for all target temperatures and directions and it consisted of loading the samples until failure, measuring the shear deformation and applied load in each sample.

To heat the samples up to the target temperatures, a *Tinius Olsen* thermal chamber was used, with interior dimensions of 605 × 250 × 250 mm^3. An average heating rate (of the air) of 14 °C/minute was applied. To guarantee that the air temperature in the interior of the oven reached the target temperature, a thermocouple (and temperature controller) from *Tinius Olsen* (Figure 3a) was used, which measured the temperature inside the chamber; a 60 minutes soaking period (to allow the temperature in the specimen to stabilize) until the beginning of the load application was adopted. Given the thickness of the sample, it was considered that the soaking period would be enough so that the sample would reach a temperature close to the air inside the chamber.

To apply the load to the sample in the *Iosipescu/V-notch* test device (Figure 3b), a hydraulic universal test machine from *Instron*, model *8800D* (Figure 3c), with a load capacity of 250 kN, was used. The tests were performed monotonically under displacement control at a test speed of 0,5 mm/min.

The position of the different points marked on each sample was measured during the test at a frequency of 5 Hz, using a video extensometer of high definition with a *Sony XCG-500E* camera and *Fujinon – Fujifilm HF50SA-1* lens, supported by a tripod (Figure 3d). The applied load and the cross-head displacement of the test machine and the position of the targets marked in the test samples were monitored by *LabVIEW* software.

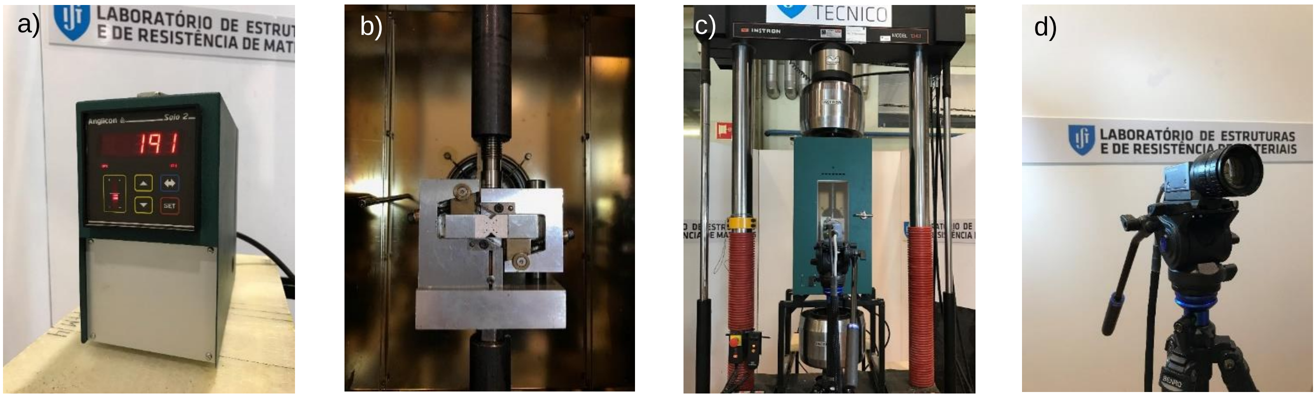

Figure 3 - *Iosipescu/V-notch* test setup: a) temperature controller *Tinius Olsen*; b) *Iosipescu* test device with a sample RT; c) hydraulic universal test machine *Instron 8800D*; d) video extensometer of high definition with a *Sony XCG-500E camera* and a *Fujinon – Fujifilm HF50SA-1* lens, supported by a tripod

3. Experimental results and discussion

3.1. DSC/TGA tests

The biomass pyrolysis products are formed by gases, liquid, and char [10]. This process can be represented by the following generic reaction,

$$Biomass + heat = \sum_{liquid} + \sum_{gas} + Char$$

Figure 4 shows the DSC/TGA tests results of one of the representative sample related to a normalized mass (-) and heat flux (mW) in function of temperature (°C).

Each one of the balsa wood constituents (cellulose, hemicellulose, and lignin) shows a temperature interval distinct for its decomposition. The cellulose decomposition involves initially the dehydration at low temperatures, visible in the initial section's curve of the mass loss. In this curve two stages are observed: a first loss with approximately 70% of mass between 250 °C and 350 °C, corresponding essentially to the hemicellulose and the cellulose degradation with a poor endothermic reaction; and a second mass loss (slower), whose magnitude varies majorly according to the lignin degradation. The samples with higher density (140,4 kg/m^3) still showed 10% to 15% of its initial mass at the end of the pyrolysis, which probably has char and ashes in its constitution as inorganic material of significant exothermal characteristics and with an elevated thermal charge.

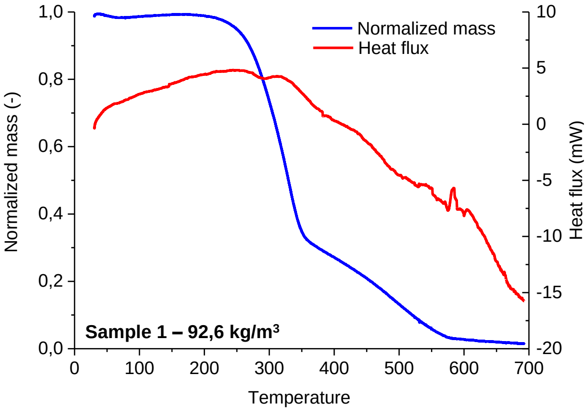

Figure 4 - Test results of one of the representative samples related to a normalized mass (-) and heat flux (mW) on the basis of temperature (°C)

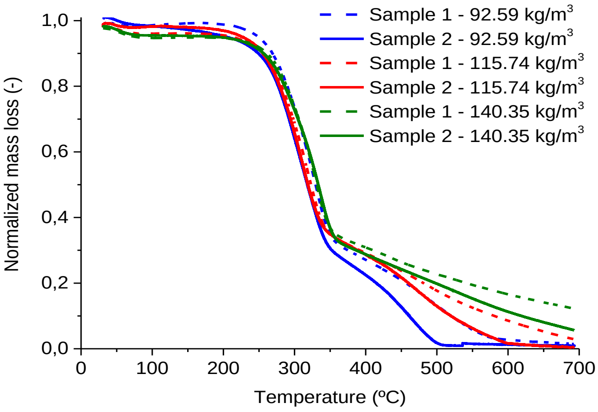

Figure 5 – Comparison of curves of the normalized mass loss (-) as a function of temperature (°C) for all samples tested

Figure 5 also shows that the first stage of mass loss corresponding essentially to the hemicellulose and cellulose degradation is similar to all densities studied. In the second stage, mainly related to the lignin degradation, a decrease in the mass loss rate occurs related to the temperature; this rate becomes lower with the increase of the balsa density, showing a bigger amount of lignin in the balsa with superior densities and more difficulty in the degradation of the lignin when the temperature rises due to its more complex structure.

The relatively rapid loss of 70% of mass should result in a substantial volume increase (expansion), associated with the production of water vapor and the release of combustible gases; this may result in degradation of the adhesion between the core and the FRP laminate of the sandwich panels in a fire situation. Volatile products, highly combustible, may still "feed" the fire.

3.2. Shear tests at elevated temperature

In the various tests, with the temperature rise, the occurrence of physical changes on the balsa wood samples was progressively verified, noticeable through the surface odour and darkness, as shown in Figure 6.

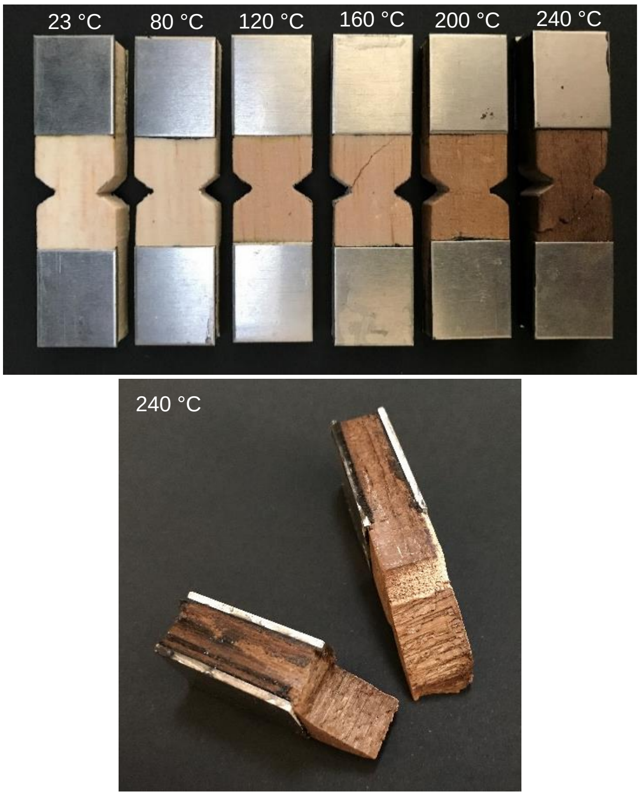

Figure 6 - Physical changes on the balsa wood with the temperature rise on the RT samples

Figure 7a and Figure 7b show the shear stress-distortion curves of samples representative of each target temperature in both main directions of the balsa. In general, balsa wood presents an initial linear response, with reduction of stiffness and load being observed before failure. Globally, the temperature rise causes a reduction of stiffness and resistance of the balsa wood. In most of the tests, the samples in RT direction showed baseline ductility superior to that of the RL samples for all temperatures. A ductility increase of the samples was observed in the tests at 120°C and 160°C in the RT direction and at 160°C in the RL direction.

Figure 8 shows the global effect of the stiffness and strength reduction with the temperature rise, illustrating the degradation with the temperature rise of the mechanical properties of balsa in shear, in both directions: G (Figure 8a) and τ_u (Figure 8b).

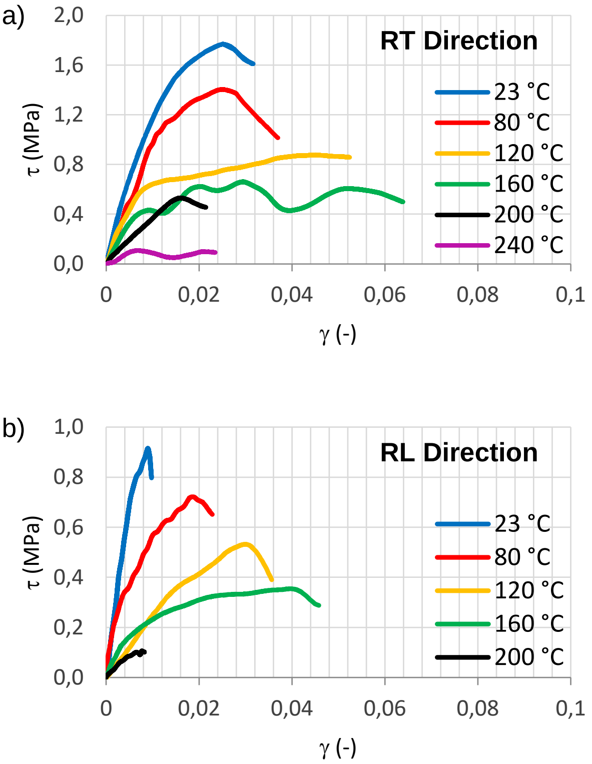

Figure 7 - Shear stress (τ) *vs.* distortion (γ) curves of representative samples of each target temperature

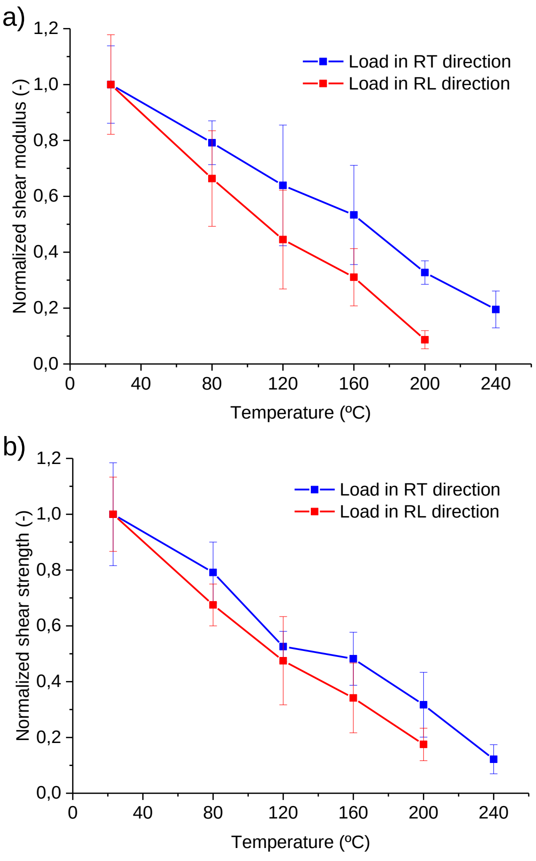

Figure 8 - Degradation of the normalized values of G and of τ_u (average and standard deviation) with temperature for the RT and RL directions

For both loading directions (related to the orientation of material fibres of the sample) the kind of failure modes considered valid correspond to those indicated in the ASTMD5379/D5379M standard [8] (for the tests with laminates composites). In the RL direction, the typical failure mode of the samples was initiated in the notch vertices and it was extended in the direction of balsa fibres, as shown in Figure 9. In the RL direction, the typical failure mode of the samples was also triggered in the notch vertices and it extended almost immediately between the notches and in the whole height of the samples in the direction of the balsa fibres, as shown in Figure 10.

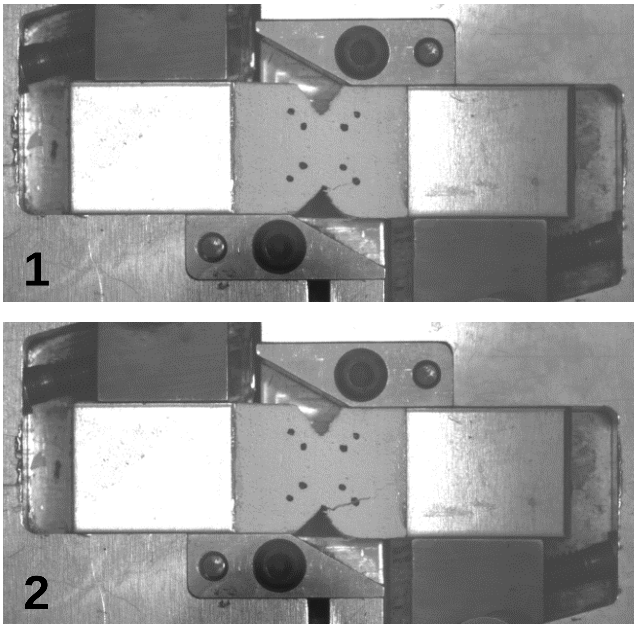

Figure 9 - Typical failure mode of the RT samples

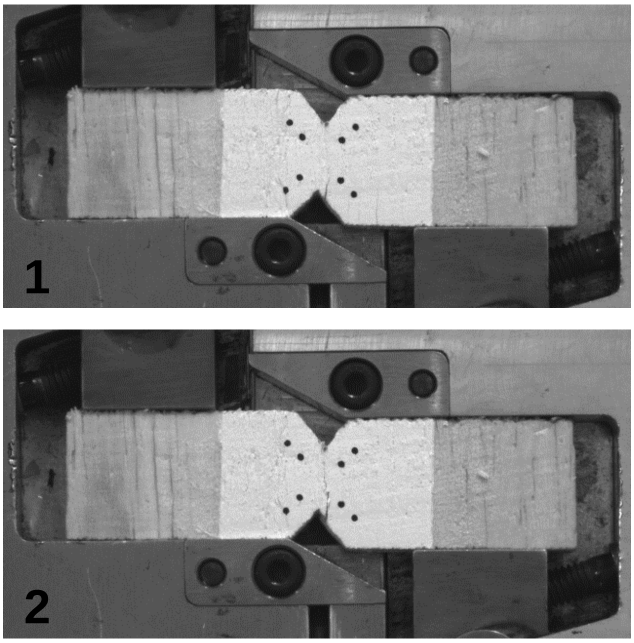

Figure 10 - Typical failure mode of the RL samples

4. Analytical modelling of properties degradation with temperature

4.1. Description of models and parameter estimation

There are several models in the literature to describe the degradation of the mechanical properties of polymeric materials with temperature, namely the ones by Gibson *et al*. [11], Mahieux *et al.* [12], Correia *et al*. [13] and Wang *et al*. [14]. In the present study, we will use these models for the balsa wood [15].

According to Gibson *et al*., the variation of mechanical properties of FRP materials with temperature can be calculated using the following equation,

$$P(T) = P_u - \frac{P_u - P_r}{2} \times (1 + \tanh[k'(T - T_{g,mech})]) \qquad (1)$$

where k' and $T_{g,mech}$ are parameters obtained by fitting the model to the experimental data, P_u is the mechanical property at room temperature (unrelaxed property) and P_r is the mechanical property after the glass transition (relaxed property), in other words, at high temperature, but before the decomposition.

In the model proposed by Mahieux *et al*. [12], the previous variation is modelled by the Weibull distribution using the following equation (where the temperature is measured in Kelvin (K)),

$$P(T) = P_r + (P_u - P_r) \times \exp[-(T/T_0)^m] \qquad (2)$$

in this equation T_0 is the relaxed temperature and m is the Weibull exponent, both parameters being also obtained by fitting the curve to the values obtained experimentally.

Correia *et al*. [13] proposed the following model to describe the effect of elevated temperature in the resistance to traction, compression and shear of pultruded GFRP laminates,

$$P(T) = P_r + (P_u - P_r) \times \left(1 - e^{Be^{C \times T}}\right) \qquad (3)$$

in this equation, the coefficients B and C are parameters of shape and scale, respectively, which are obtained by the same way of the previous models, through the fitting to the experimental values.

Wang *et al*. [14] suggest the following model, initially developed for metals subjected to elevated temperature, which the authors applied with success to describe the tensile resistance of CFRP (Carbon Fibre Reinforced Polymer) pultruded laminates,

$$P(T) = P_u \times \left[A - \frac{(T - B)^n}{C}\right] \qquad (4)$$

in which the coefficients A, B, C and n can be estimated for different temperatures ranges.

4.2. Results and discussion

Figure 11 shows the results obtained by fitting the previous models to the experimental values of the shear modulus for the various temperatures in the directions RT (Figure 11a) and RL (Figure 11b). In the same way, in Figure 12 the shear strength fitted by those models is compared to the experimental values for directions RT (a) and RL (Figure 12b). Table 1 lists the parameters estimated for all models, obtained through the fitting to the experimental values (G and τ_u) with the temperature rise for the RT and RL directions.

For the shear modulus in RT direction, the model by Wang *et al*. presents the best fit with an AMPE (absolute mean percentage error) of 10,1%. In the RL direction, the model by Correia *et al*. presents the best fit with an AMPE of 11,6%.

For the shear strength in the RT direction, as for the shear modulus, the most accurate model is the one by Wang *et al*. with an AMPE of 9,9%. In the RL direction as for the shear modulus, the most precise model in reproducing shear strength is the one by Correia *et al*. with an AMPE of 10,4%.

A linear model adapted from the Wang *et al.* model showed to be able to describe with adequate precision the degradation of the mechanical properties of balsa in shear with temperature. This model pointed to practically null the values of shear modulus and shear strength at temperatures of 270 °C for the RT direction and 230 °C for the RL direction.

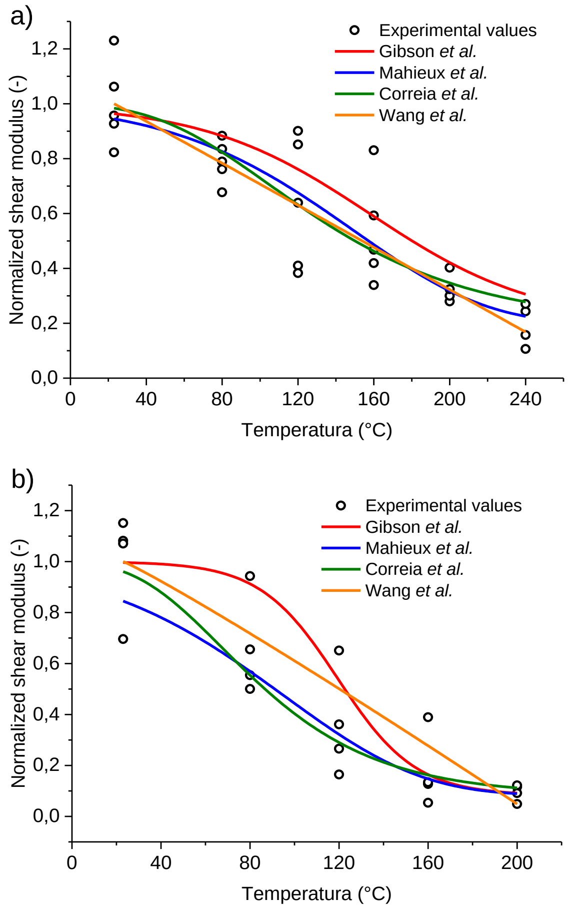

Figure 11 – Comparison of the different models and the experimental values of the shear modulus as a function of temperature: a) in the RT direction; b) in the RL direction.

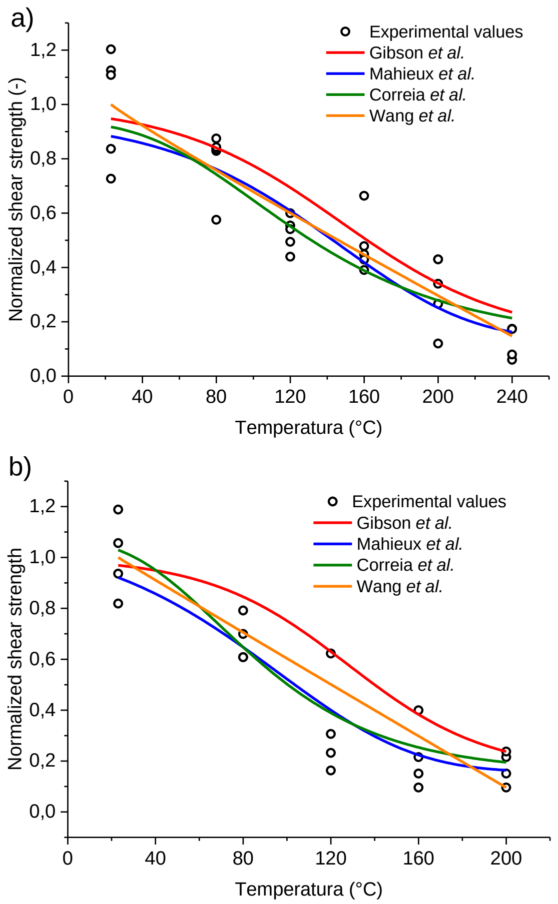

Figure 12 - Comparison of the different models and the experimental values of the shear strength as a function of temperature: a) in the RT direction; b) in the RL direction.

Table 1 - Parameters estimated for all models through the fitting to the experimental values (shear modulus and shear strength) (for RT and RL directions).

Model	**Parameter**	**RT Direction**		**RL Direction**	
		G	τ_u	**G**	τ_u
Gibson *et al.* [11]	k' (-)	0,01130	0,01102	0,02859	0,01560
	$T_{g,mech}$ (°C)	158,1	147,2	119,4	127,9
	AMPE (%)	13,27	12,04	15,63	16,73
Mahieux *et al.* [12]	T_0 (K)	432,0	430,3	376,9	377,6
	m (-)	7,0	7,0	7,0	7,0
	AMPE (%)	10,29	10,49	12,67	10,41
Correia *et al.* [13]	B (-)	- 5,7051	- 5,2368	- 5,7123	- 5,2527
	C (-)	- 0,0166	- 0,0164	- 0,0259	- 0,0241
	AMPE (%)	10,70	10,39	11,64	10,41
Wang *et al.* [14]	A (-)	1,0	1,0	1,0	1,0
	B (-)	23,0	23,0	23,0	23,0
	C (-)	270,9	185,3	270,9	185,3
	n (-)	1,006	0,940	1,073	0,989
	AMPE (%)	10,14	9,85	14,89	12,88

5. Numerical modelling of the thermomechanical behaviour of GFRP-balsa sandwich panel

5.1. Description of models

In the numerical study a finite element thermo-mechanical model of a sandwich panel composed by two faces in GFRP (with density of 1700 kg/m^3) and a core in balsa wood *Baltek® SB 50* (end grain) with the average density of 94 kg/m^3 was developed using Abaqus software. The panel has 1200 mm of length, 600 mm of width and 134 mm of height (120 mm of the core and 7 mm of each laminate) (Figure 13). This cross-section was defined based on a previous study carried out at IST [16] and aiming at using those panels in building floors. The finite element mesh used comprised 8-node solid elements and was defined based on a mesh sensitivity study.

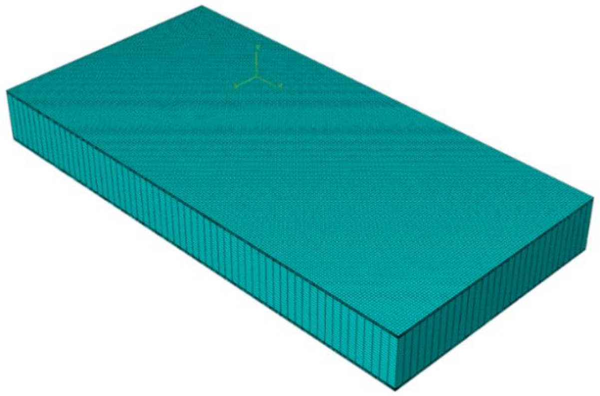

Figure 13 - Sandwich panel composed of two faces in GFRP and balsa wood as core material.

In the thermal analysis, to simulate a possible fire scenario in a building compartment, the curve of the standard fire of ISO 834 was used in which the inferior face of the panel in GFRP was exposed to the temperature of fire gases (°C) in function of time (min) being the other face at room temperature (20 °C). To implement a solution for fire protection for the sandwich panel, a gypsum laminate of 15 mm of thickness (adherent to the inferior face of the panel) was considered.

All the materials were modelled considering the variation of their thermophysical and mechanical properties with temperature, based on the literature [5, 7, 16, 17] and on the obtained data in the present study (in the case of the mechanical properties of the balsa).

For the thermal model, the heat exchanges by radiation and convection in the hot and cold faces considered, as well as the exchanges by conduction on solid media.

In the mechanical model, in order to illustrate the application of the analytical models developed in the present study (and the mechanical properties obtained in the experiments), a sandwich panel was considered with the previously mentioned cross-section, simply supported in a span of 1200 mm and subjected to a unit uniformly distributed load (1 kN/m^2) on its top surface.

5.2. Results and discussion

Figure 14a presents the variation of temperature in function of time (min) without and with protection of the panel (dashed line and continuous line, respectively) of 5 distinct points of a panel section: the A point on the centre of the hot surface laminate; the B point on the core at distance of 1/10 of the core thickness to the hot surface laminate; the C point on the centre of the core; the D point at distance of 9/10 of the core thickness to the cold surface laminate. Figure 14b shows the variation of the midspan vertical displacement (mm) of the central point of the average line cross-section of the panel without and with protection to fire in function of time (min).

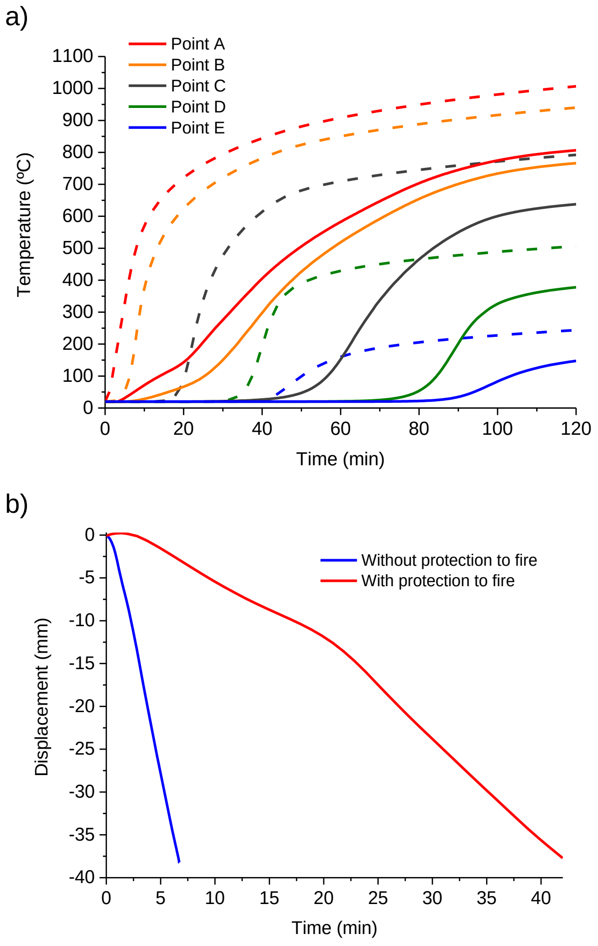

Figure 14 - Comparison of the numerical modelling results: a) thermal analysis; b) mechanical analysis

Figure 14a shows, for the panel without additional protection, that the laminate temperature of the hot surface quickly increases with time, reaching its glass transition temperature after 1.5 minutes; in GFRP laminates that temperature depends on many factors (such as the production process or the resin matrix), being about 100 °C. This laminate reaches its decomposition temperature (350-450 °C) in about 7 minutes. The core centre in balsa wood reaches 250 °C, the temperature for which it presents almost null resistance and stiffness (shear), at the end of approximately 20 minutes. It was also verified that the balsa near to the laminate exposed to fire reaches this temperature after 8 minutes.

In the panel without protection, until the first minute, the displacement as a function of time presents a nonlinear behaviour, with a maximum of 5 mm. Until the possible panel failure (after 6,7 minutes, when the model stopped converging, constituting a short period of time), the displacement increase with time presents a nearly linear shape, until a maximum of approximately 38 mm (~ L/32, being L the span) (Figure 14b).

The possible failure of the panel without protection seems to occur when the face exposed to fire is at about 440 °C. This temperature is within the range of temperatures for which the decomposition of GFRP takes place. The balsa wood near this face is at a temperature for which its resistance and stiffness is almost null (250 °C).

With an additional protection of the sandwich panel, there is a significant improvement of its thermal and mechanical response. The unprotected panel can be classified as EI60 and after the use of protection with a gypsum laminate, it can be classified as EI120 (assuming that, in light of the reached temperatures in the hot face and, since guaranteeing a good peripheral isolation, gas emission through the unexposed face will not occur).

Figure 15 illustrates outputs of the thermal (Figure 15a) and mechanical models (Figure 15b) generated by the *Abaqus 6 .13* software at different instants.

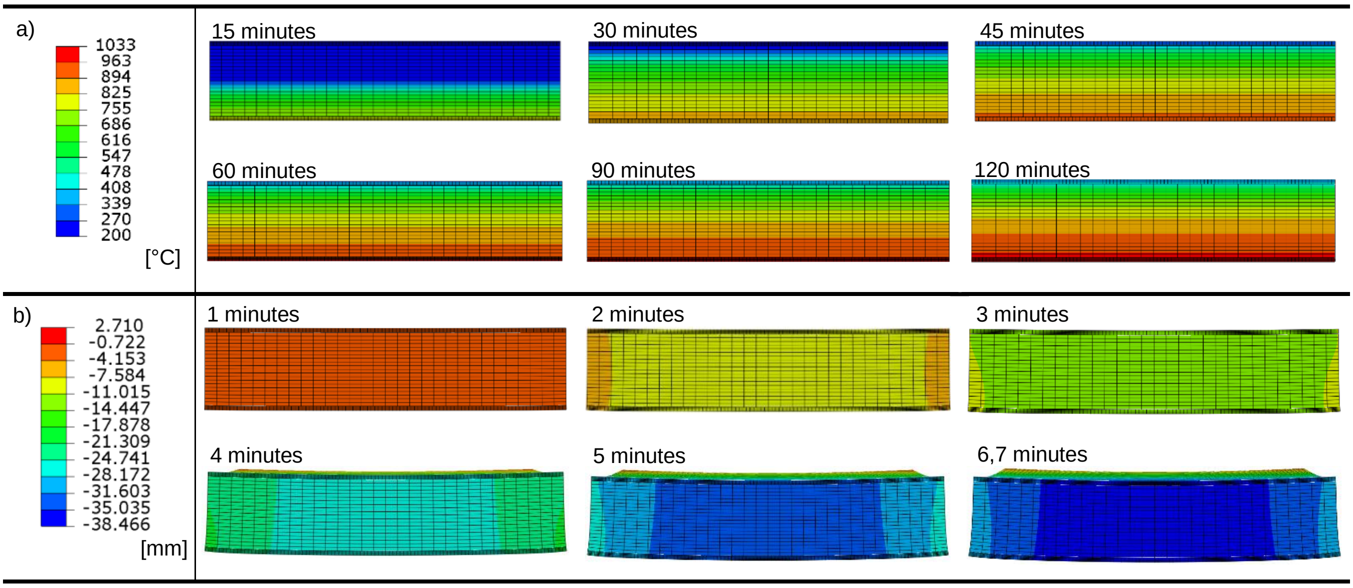

Figure 15 - Results of the numerical model: a) temperature variation through the panel for the cold face in a fire scenario with 2 hours of duration; b) variation of the vertical displacement (cross-section at the central span of the panel), until possible failure of the unprotected panel (6,7 minutes).

6. Conclusions

With the present experimental, analytical and numerical study, concerned with the behaviour at elevated temperature of balsa wood as a core material of composite sandwich panels for structural civil engineering applications, it was possible to obtain the following main conclusions:

1. The mass loss of the balsa wood is developed in two stages (as described in the literature for other wood products): the first loss, causing a mass loss of about 70%, between 250 °C and 350 °C, corresponding essentially to the hemicellulose and the cellulose degradation, and a second mass loss, corresponding to the lignin degradation.

2. The stiffness and strength of the balsa wood in shear are significantly affected with the increase of temperature. For temperatures of 240 °C in the RT direction and of 200 °C for the RL direction, those properties became lower than 20% of their value at a room temperature.

3. The degradation of the mechanical properties of the balsa wood in shear with the temperature increase for the RT direction is described with more precision by the model of Wang *et al*. and for the RT direction by the Correia *et al*. model.

4. A linear model adapted from the Wang *et al*. model showed to be able to describe with adequate precision the degradation of the mechanical properties in shear in function of the temperature of the balsa wood.

5. In a possible fire scenario in a building compartment with floors made with unprotected GFRP-balsa sandwich panels, the laminate temperature of the hot surface quickly rises with time, reaching, at the end of 1.5 minutes, its glass transition temperature (100 °C), and reaching its decomposition temperature (350-450 °C) at about 7 minutes. At the end of nearly 20 minutes, the core centre in balsa wood reaches 250 °C, temperature for which it presents almost null shear strength and stiffness. This response can be significantly improved by adopting a gypsum board as thin as 15 mm as fire protection.

6. According to the European regulation, based on the temperatures in the cold face, the unprotected panel can be classified as EI60, with a classification of EI 120 being obtained after the additional protection.

7. References

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