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ORIGINAL ARTICLE

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High-temperature mechanical properties and thermal recovery of balsa wood

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Abstract This article presents an experimental study into thermal softening and thermal recovery of the compression strength properties of structural balsa wood (*Ochroma pyramidale*). Balsa is a core material used in sandwich composite structures for applications where fire is an ever-present risk, such as ships and buildings. This article investigates the thermal softening response of balsa with increasing temperature, and the thermal recovery behavior when softened balsa is cooled following heating. Exposure to elevated temperatures was limited to a short time (15 min), representative of a fire or postfire scenario. The compression strength of balsa decreased progressively with increasing temperature from 20° to 250°C. The degradation rates in the strength properties over this temperature range were similar in the axial and radial directions of the balsa grains. Thermogravimetric analysis revealed only small mass losses (<2%) in this temperature range. Environmental scanning electron microscopy showed minor physical changes to the wood grain structure from 190° to 250°C, with holes beginning to form in the cell wall at 250°C. The reduction in compression properties is attributed mostly to thermal viscous softening of the hemicellulose and lignin in the cell walls. Post-heating tests revealed that thermal softening up to 250°C is fully reversible when balsa is cooled to room temperature. When balsa is heated to 250°C or higher, the post-heating strength properties are reduced significantly by decomposition processes of all wood constituents, which irreversibly degrade the wood microstructure. This study revealed that the balsa core in sandwich composite structures must remain below 200°–250°C when exposed to fire to avoid permanent heat damage.

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Introduction

Balsa wood (*Ochroma pyramidale*) is commonly used as the structural core material in sandwich composites. Balsa core sandwich composites are used in load-bearing structures in ships, buildings, and offshore platforms. For example, sandwich materials composed of fiber–polymer laminate skins and balsa wood are used in the hull, superstructure, and masts of naval ships. A concern with using sandwich composites in load-bearing structures is the heat damage and softening that occurs in the event of fire. The stiffness and strength properties of the balsa core and laminate skins are reduced by thermal softening, heat damage (e.g., delaminations and cracks), and decomposition.[1] Sandwich composites exposed to high-temperature fires can suffer extreme heat distortion and collapse within a short time (<10 mins).[2–12]

Thermal softening, decomposition, and failure of polymer laminates used for face skins have been extensively studied, and models and data are available to determine the loss in skin properties during fire.[1] Softening and failure of the balsa core is less well understood, but is critical to the structural survivability of sandwich composites in fire. The structural properties of sandwich composites under through-thickness compression and in-plane shear loads are dependent on the core properties, and any thermal softening or decomposition of balsa will reduce these properties. A limited amount of data is available on the thermal softening of wood while exposed to high temperatures.[13–17]

Another consideration in the fire behavior of sandwich composite materials is their residual properties after the fire is extinguished.[2] Again, models and data are available to determine the residual stiffness and strength properties of laminate skins following fire,[1] but there is little information on the postfire properties of balsa wood following exposure to high-temperature fire. Most published research has

focused on the effect of heat treatment up to 250°C of timber boards used in construction (e.g., pine and spruce) for increased resistance to fungal attack,[18–20] but this temperature is below that generated by most fires.

This article presents an experimental investigation into the mechanical properties, physical degradation, and decomposition of balsa wood at high temperatures. The compression strength properties and softening behavior of balsa during and after exposure to high temperatures for a short time (15 min) were determined to assess its structural performance during and following fire. Reductions in the high-temperature strength properties are related to physical transformations and phase changes of the balsa grains.

Materials and methods

Balsa wood

Structural end-grain balsa wood (Baltek SB.100) was studied; this is the core material for sandwich composites used in naval ships and other structural applications. The average density of the balsa was 150 kg/m^3, although there was a large amount of variability (a standard deviation of 45 kg/m^3) within a single panel of as-received wood, which is typical for balsa and was taken into account during the mechanical testing. The initial moisture content of the balsa wood was 2%–8%, depending on laboratory atmospheric conditions.

Compression testing

The compression strength properties of the balsa were determined along the grain (axial direction) and across the grain (radial direction) using cube specimens cut from a large panel, as shown in Fig. 1. The specimens were 30 mm long, 30 mm wide, and 15 mm thick, and they were loaded at a constant compression rate of 0.5 mm/min in accordance with ASTM C365-94. Balsa specimens were compression tested at different temperatures between 20° and 300°C to determine their high-temperature properties. Specimens were also tested at room temperature following heating to between 20° and 450°C to determine their postfire properties. For both test series, specimens were heated for 15 min to ensure uniform temperature distribution throughout the material as established using thermocouple measurements. A total of 10–15 specimens (because of the large density variation in balsa) were tested for each heating condition to establish the density–strength relationship.

The mechanical properties of wood are dependent on the density, and therefore the measured properties were adjusted to account for differences in density between specimens. The compression strength in the axial (σ_{axial}) and radial (σ_{radial}) directions were evaluated at the average density of ρ_o = 150 kg/m^3 using the relationships:

$$\sigma_{axial} = \alpha\left(\frac{\rho}{\rho_o}\right) \quad (1)$$

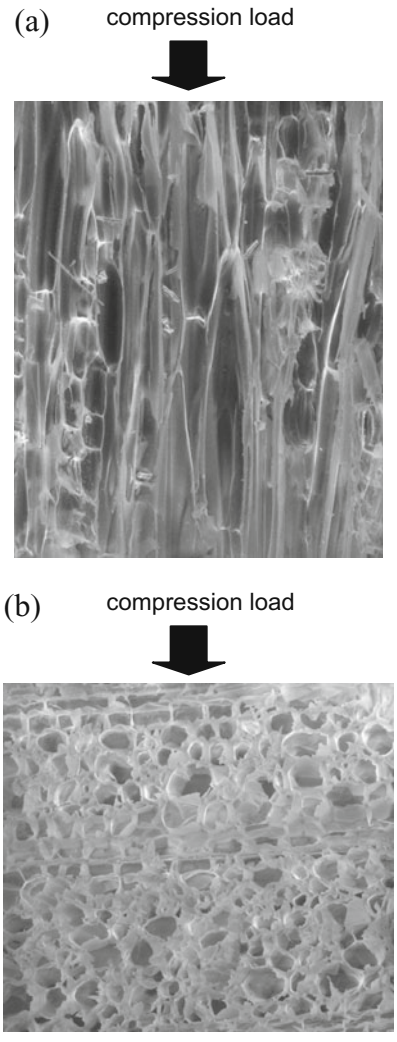

Fig. 1. Compression loading in **a** axial and **b** radial directions of the balsa. The difference in wood cell structure in the two directions is evident

and

$$\sigma_{axial} = \beta\left(\frac{\rho}{\rho_o}\right)^2 \quad (2)$$

where α and β are scaling constants.[21]

Thermogravimetric analysis

Thermogravimetric analysis (TGA) was used to measure the dehydration and decomposition behavior of the balsa with increasing temperature (40°–800°C). TGA was performed in a nitrogen atmosphere using disk-shaped balsa specimens (6.2 mm in diameter, 1.50–1.85 mm high). Two types of TGA tests were performed using a Netzsch STA 449 F1 Jupiter Simultaneous Thermogravimetric Analyzer/Differential Scanning Calorimeter (TGA/DSC) to measure separately the dehydration and decomposition processes. The dehydration of balsa was determined by TGA performed at a heating rate of 20°C/min over the range 40°–180°C. This analysis captures the evaporation of water from

the balsa, but stops before the decomposition process, as indicated by significant mass loss. Decomposition was studied using specimens that had been dried at 110°C before TGA testing. TGA was then performed by heating the specimen at 20°C/min to between 40° and 800°C.

Microstructural analysis

The microstructure of balsa at elevated temperatures was examined using an environmental scanning electron microscope (FEI Quanta 600 FEG). The microscope was equipped with a heating stage that allowed direct observation of specimens at high temperature. Balsa specimens were examined in the axial and radial directions at different temperatures up to 550°C at a heating rate of 20°C/min.

Results and discussion

Figure 2 shows the effect of temperature on the compression strength in the axial and radial grain directions of balsa. The strength in both directions decreased at a quasi-linear rate with increasing temperature. By 250°C, the properties were approximately 20% of those at room temperature. As expected, the compression properties are higher in the axial direction because the compression load is applied parallel to the microfibrils in the middle section of the secondary cell wall.[21] The crystalline cellulose chains in the microfibrils are stiff and strong and therefore able to support relatively high loads. The radial properties are determined mainly by the hemicellulose and lignin that bind the microfibrils; these materials are weaker than crystalline cellulose. The properties are also lower in the radial direction because of the voids and the lack of continuity to the cell structure in this direction.

While the high-temperature strength properties are higher in the axial direction, the average softening rate of the balsa is not dependent on the load direction. Figure 3 compares the normalized high-temperature strengths of balsa measured in the axial and radial directions. The normalized strength is the high-temperature strength divided by the room temperature strength of the wood when measured in the same direction. Balsa loses strength at the same constant rate in both directions, which suggests that the softening processes are the same in the axial and radial directions.

The mass loss–temperature curve for balsa wood measured using TGA at 20°C/min is shown in Fig. 4. It was found that balsa loses approximately 2% mass over the temperature range 60°–150°C. This mass loss is mostly attributed to evaporation of water, and as such establishes the water content of the balsa wood. Other volatile products resulting from hemicellulose decomposition in this temperature range were assumed to be of minor importance because the mass loss was shown to be mostly reversible through moisture uptake from the atmosphere within the laboratory environment. Using TGA, material decomposition was found to begin at 190°C, although decomposition was rela-

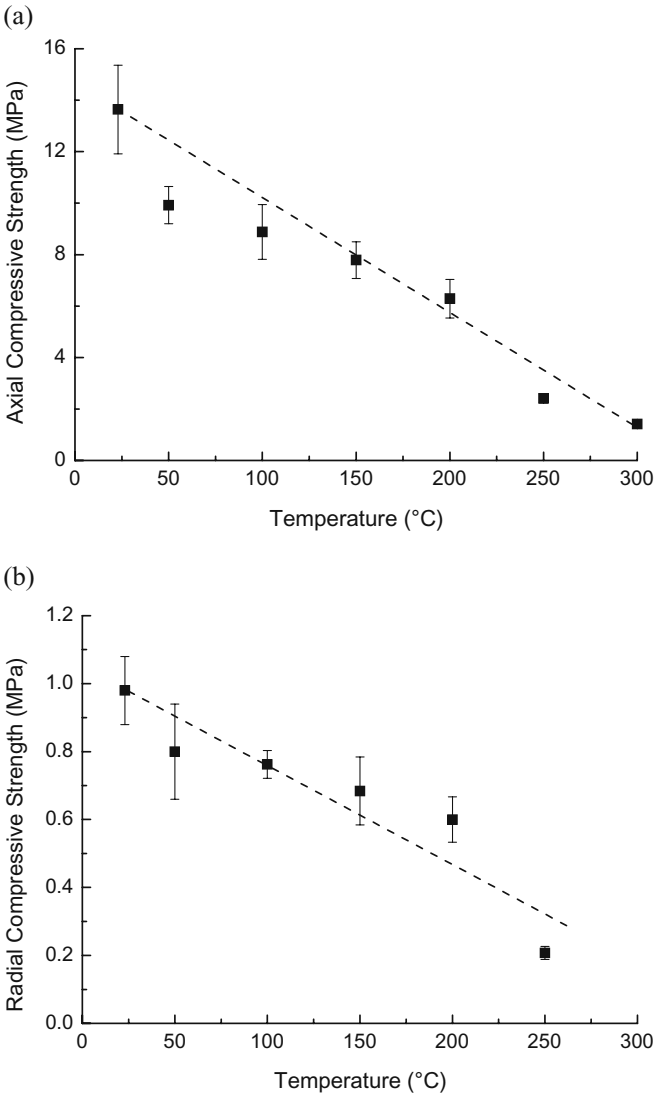

Fig. 2. Effect of temperature on the compression strength measured in **a** axial and **b** radial directions

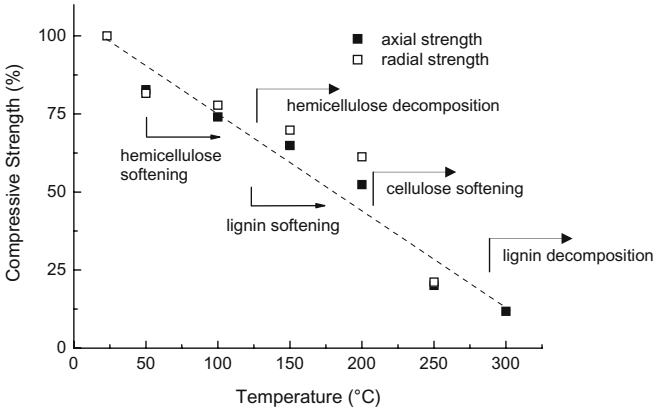

Fig. 3. Normalized high-temperature strength of balsa wood in the axial and radial directions

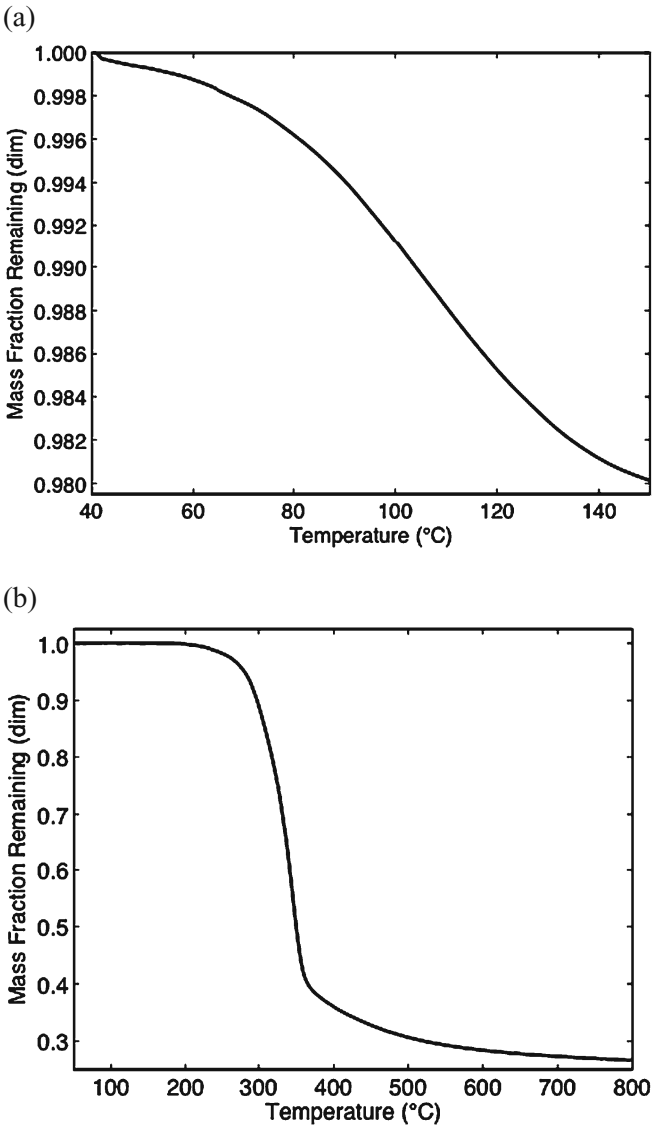

Fig. 4. Mass loss–temperature curves for **a** water evaporation and **b** decomposition for balsa wood measured using thermogravimetric analysis at 20°C/min

tively slow until 350°–375°C, when a rapid rise occurred in the mass loss rate. From Fig. 2, it can be seen that at 250°C, strength properties have decreased by 80% compared to those at room temperature. With less than 2% decomposition mass loss occurring by 250°C, thermal softening processes appear to be the primary mechanism for strength loss up to approximately 250°C. Softening processes in the temperature range below 250°C are generally attributed to the modification of hemicellulose; this is the first such change to occur and reduces the load-sharing capacity of the lignin–hemicellulose matrix.[19] The lower thermal stability of hemicellulose compared to cellulose is usually explained by its lack of crystallinity.[18] Typical temperature ranges[13] for softening and decomposition of wood constituents are indicated in Fig. 3. Decomposition of the hemicellulose below 250°C is assumed to be minimal in our experiments due to the short exposure times.[20]

Environmental scanning electron microscopy (ESEM) images of the balsa microstructure in the axial and radial directions at different temperatures are presented in Fig. 5. ESEM analysis was performed at different temperatures up to 550°C. No physical change to the wood structure was observed over the temperature range 20°–190°C. The small loss in mass between 60° and 180°C due to water evaporation did not cause any observable change to the cell structure. The first sign of microstructural damage was detected at ~190°C, when slight changes occur in the structure of the cell walls. Holes begin forming in the cell walls due to decomposition at 250°C. Figure 6 contains a series of ESEM images taken from 190°–270°C showing the onset of decomposition and the formation of cell wall holes. The cell wall structure broke down rapidly with increasing temperature between 250° and 450°C, causing the wood to shrink. No significant changes were observed to the heavily decomposed microstructure above 450°C, when the cell walls are composed mostly of carbonaceous char. Quantitative analysis of the ESEM images revealed that the void fraction increased and the wood grain density (number of grains per unit area) decreased between 250° and 450°C due to decomposition, as shown in Fig. 7.

Based on thermogravimetric and microstructural analyses, it appears that the decomposition and physical breakdown of the cell wall structure does not have a significant influence on the reduction of the high-temperature properties of balsa. The properties are already greatly reduced before decomposition and microstructural damage occur to the grain structure. The high-temperature strength loss is caused mostly by thermal softening of the hemicellulose (which begins at 50°C) and lignin (above 120°C), which both undergo a glass transition from rigid to viscous states in the cell walls.[22,23] The temperature at which glass transition softening of the cellulose and lignin begins is indicated in Fig. 3, although it is dependent on the moisture content of the wood. Large losses in strength occur over the temperature ranges at which hemicellulose and lignin soften. It is of interest to note that the scatter in the experimental results decreases significantly at temperatures above 250°C. This is attributed to the fact that decomposition of the balsa wood eliminates grain size variability in the material.

The residual strength of balsa wood after it has been heated and then cooled back to room temperature was also measured. The effect of heating temperature on the residual compression strengths of the balsa at 20°C is shown in Fig. 8. The strength of balsa did not change significantly by heating and subsequent cooling until the maximum temperature exceeded 250°C, above which the properties decreased rapidly due to irreversible decomposition of the grain structure, as shown by the ESEM analysis. This postfire performance is significantly better than the postfire compression properties reported for thermally treated timbers of high density,[18–20] although the heat-treatment times for these studies were significantly longer (2–6 h). Heat-treatment times in the present study were kept to a maximum of 15 min to allow for the modeling of fire scenarios in which temperature exposure below 250°C will be relatively short. It has been reported that cellulose and

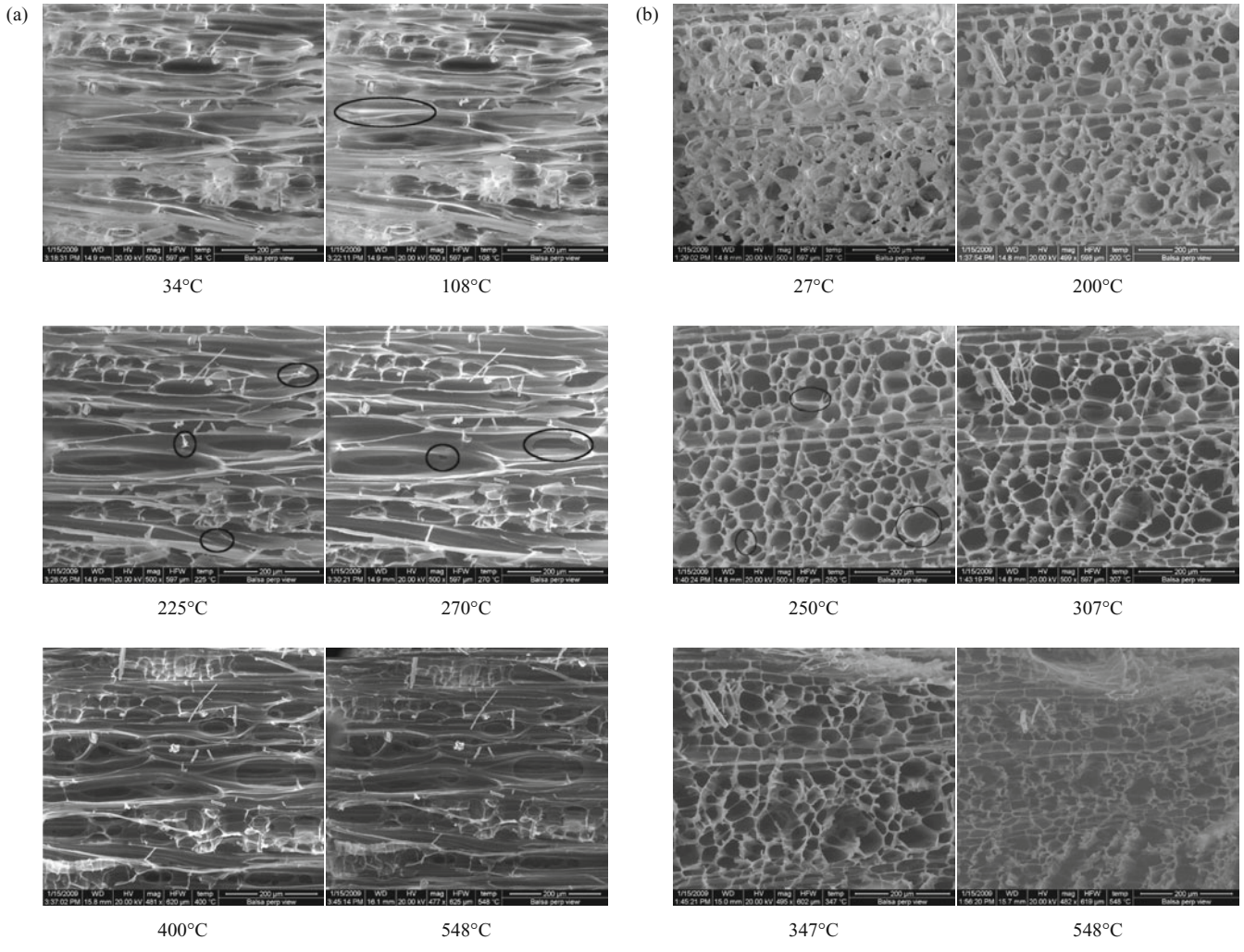

Fig. 5. Environmental scanning electron microscopy images of balsa in **a** axial and **b** radial directions. *Circled regions* indicate locations of initial decomposition of the cell walls

lignin do not depolymerize until 210° and 280°C, respectively,[13,24] and therefore these wood components will recover when cooled from below these temperatures. The loss of water, which occurs between 60° and 180°C, is also recoverable under standard atmospheric conditions at 20°C. Water within the air (humidity) is reabsorbed by the dried wood within a short time (less than 24 h). The onset of hemicellulose decomposition in wood occurs at around 120°C,[13,18,24] but in this study it was found not to significantly affect the postfire properties of balsa for short exposure times (15 min), and significant mass changes were not observed in this temperature range, which is in agreement with data from the literature.[20] It appears, therefore, that balsa wood has good postfire mechanical properties for maximum exposure temperatures below 250°C.

Conclusions

The compression strength of balsa decreases at a quasi-linear rate with increasing temperature up to the point of decomposition (250°C). The normalized thermal softening rate between 20° and 250°C is the same in the axial and radial directions of the grain structure, which indicates that the loss in strength in both directions is determined by the same softening process. The wood is nearly completely softened (with 90% loss in strength) at the decomposition temperature (250°C), and therefore softening by pyrolysis has a small influence on the loss in high-temperature strength. The cellular structure of the balsa does not change significantly with increasing temperature to the point of decomposition, and therefore physical changes of the wood have no influence on the loss in high-temperature strength. The reduction in high-temperature strength is due mainly to softening of the hemicellulose and lignin, which undergo glass transition phase changes beginning at ~50° and 120°C, respectively. This reveals that the core properties of sandwich composite structures containing a balsa core will undergo significant softening at these temperatures due to fire. The loss in strength up to the point of decomposition was reversible for the short-term exposure investigated, and the strength fully recovered when cooled back to room temperature. This is because the glass transition phase

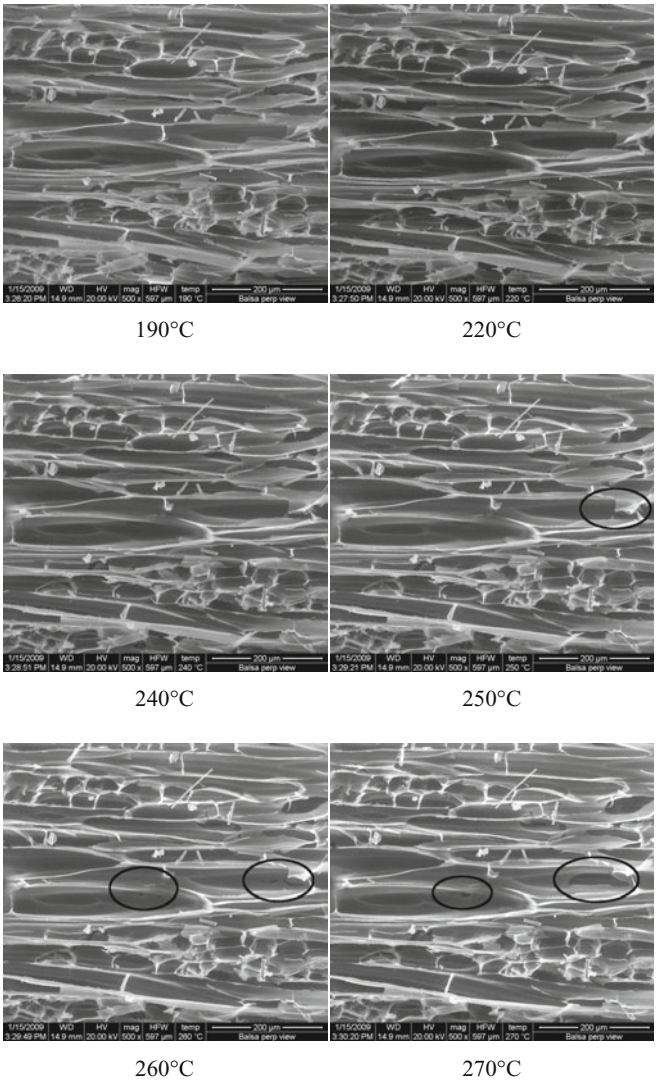

Fig. 6. Axial view of the wood showing the onset of decomposition. *Circles* identify positions of cell wall holes formed by decomposition

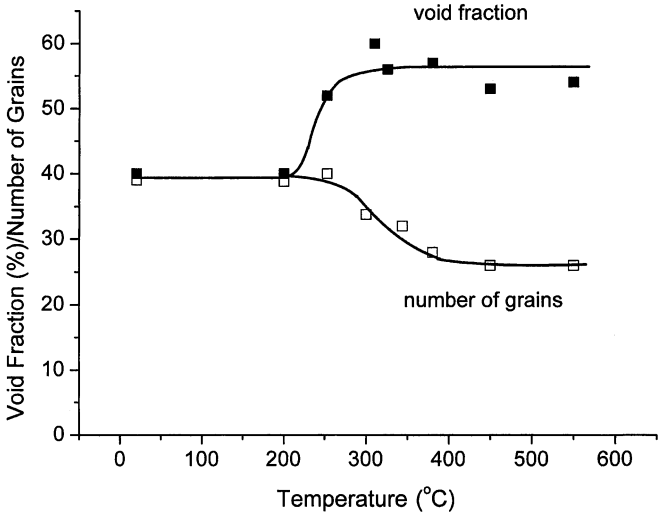

Fig. 7. Effect of temperature on the void fraction and total number of grains within a fixed volume of balsa wood

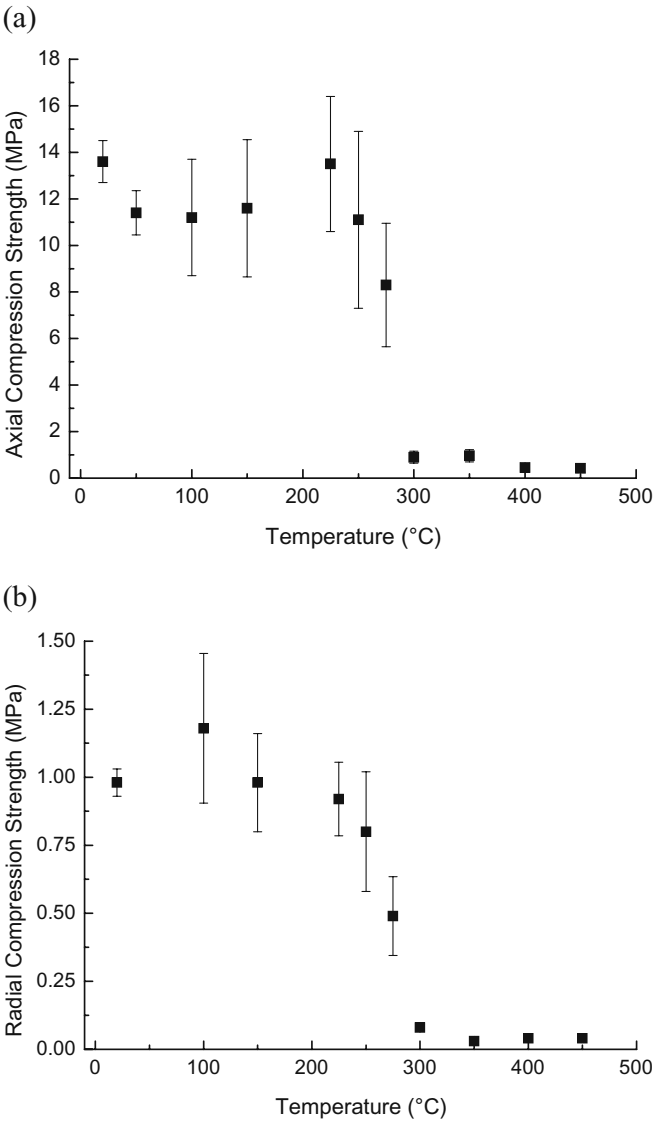

Fig. 8. Effect of temperature on the residual compression strength measured in **a** axial and **b** radial directions at 20°C after heating to an elevated temperature for 15 min

change of the hemicellulose and lignin is a reversible process, and these materials recover their stiffness and strength when cooled. This suggests that the balsa core in sandwich composites will not be permanently damaged by fire, provided the temperature does not exceed the decomposition temperature (250°C).

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References

1. Mouritz AP, Gibson AG (2006) Fire properties of polymer composite materials. Springer, Dordrecht

2. Looyeh MRE, Rados K, Bettess P (2001) Thermomechanical response of sandwich panels to fire. Finite Elem Anal Des 37:913–927
3. Mouritz AP, Gardiner C (2002) Compression properties of fire-damaged polymer sandwich composites. Composites 33A:609–620
4. Lattimer BY (2004) Large-scale fire resistance tests on sandwich composite materials. In: Proceedings of SAMPE 04. Long Beach, CA, May 16–20, 2004
5. Birman V (2005) Thermally induced bending and wrinkling in large aspect ratio sandwich panels. Composites 36A:1412–1420
6. Birman V, Kardomateas GA, Simitses GJ, Li R (2006) Response of a sandwich panel subjected to fire or elevated temperature on one of the surfaces. Composites 37A:981–988
7. Feih S, Mathys Z, Gibson AG, Mouritz AP (2008) Modelling compressive skin failure of sandwich composites in fire. J Sandw Struct Mater 10:217–245
8. Krysl P, Ramroth WT, Steward LK, Asaro RJ (2004) Finite element modeling of fibre-reinforced polymer sandwich composites exposed to heat. Int J Num Meth Eng 61:49–68
9. Gu P, Asaro RJ (2008) Distortion of polymer matrix composite panels under transverse thermal gradients. Comp Struct 82:413–412
10. Gu P, Asaro RJ (2008) Wrinkling of sandwich polymer matrix composite panels under transverse thermal gradients. Fire Saf J 43:151–160
11. Gu P, Asaro RJ (2008) Designing polymer matrix composite panels for structural integrity in fire. Compos Struct 84:300–309
12. Gu P, Asaro RJ (2009) Designing sandwich polymer matrix composite panels for structural integrity in fire. Compos Struct 88: 461–467
13. Schaffer EL (1973) Effect of pyrolytic temperatures on the longitudinal strength of dry Douglas fir. J Test Eval 1:319–332
14. Irvine GM (1985) The significance of the glass transition of lignin on thermomechanical pulping. Wood Sci Technol 19:139–149
15. Uhmeier A, Morooka T, Norimoto (1998) Influence of thermal softening and degradation on the radial compression behaviour of wet spruce. Holfforschung 52:77–81
16. Furuta Y, Kohara M, Kanayama K (1999) Thermal-softening properties of water-swollen wood. VI. The change of thermal-softening properties due to lignification with moso bamboo as a model material. Mokuzai Gakkaishi 45:193–198
17. Lenth CA, Kamket FA (2001) Moisture dependent softening behaviour of wood. Wood Fiber Sci 33:492–507
18. Yildiz S, Gezer ED, Yildiz UC (2006) Mechanical and chemical behaviour of spruce wood modified by heat. Build Environ 41: 1762–1766
19. Boonstra MJ, Van Acker J, Tjeerdsdma BF, Kegel EV (2007) Strength properties of thermally modified softwoods and its relation to polymeric structural wood components. Ann Forest Sci 64:679–690
20. Esteves BM, Pereira HM (2009) Wood modification by heat treatment: A review. BioResources 4:370–404
21. Easterling KE, Harryson R, Gibson LJ, Ashby MF (1982) On the mechanics of balsa and other woods. Proc R Soc London, A383: 31–41
22. Salmen L (1984) Viscoelastic properties of in situ lignin under water-saturated conditions. J Mater Sci 19:3090–1096
23. Szczesniak L, Rachocki A, Tritt-Goc J (2008) Glass transition temperature and thermal decomposition of cellulose powder. Cellulose 15:445–451
24. Ramiah MV (1970) Thermogravimetric and differential thermal analysis of cellulose, hemicellulose, and lignin. J Appl Polymer Sci 14:1323–1337