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Combustion performance of engineered bamboo from cone calorimeter tests

Qingfeng Xu[1] · Lingzhu Chen[1,2] · Kent A. Harries[3] · Xiangmin Li[1]

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Abstract The combustion and charring properties of two types of engineered bamboo for structural applications: laminated bamboo sheets and bamboo scrimber were investigated through cone calorimeter tests conducted at three levels of heat flux, 25, 50 and 75 kW/m^2. The test was conducted with the grain both perpendicular and parallel to incident heat flux. The ignitability and combustibility parameters of these two types of engineered bamboo were calculated and the time to ignition, heat release and mass loss rates, specific extinction area, effective heat of combustion, and carbon monoxide and carbon dioxide yield were compared. Based on observations for timber, the average measured charring rates from the cone calorimeter tests at a heat flux of 50 kW/m^2 and exposure time of 30–60 min were taken as equivalent charring rates for standard furnace tests and compared with those promulgated by European and Australian standards. Bamboo scrimber, having a density almost twice that of laminated bamboo, demonstrated superior fire performance in all parameters considered and approached the performance of a representative hardwood. The orientation of the grain was observed to have negligible influence on their charring performance for laminated bamboo, while for bamboo scrimber, the charring rate when the grain was perpendicular to the incident heat flux was slightly smaller than when the grain was parallel to incident heat flux. Finally, this study demonstrates the utility of the relatively inexpensive cone calorimeter test, for the rapid assessment of combustion and particularly charring performance of bamboo.

✉ Kent A. Harries
kharries@pitt.edu

[1] Shanghai Key Laboratory of Engineering Structure Safety, Shanghai Research Institute of Building Sciences, Shanghai 200032, China

[2] College of Civil Engineering, Tongji University, Shanghai 200092, China

[3] Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA 15261, USA

1 Introduction

Bamboo has many advantages as a construction material. It is a fast-growing, sustainable renewable resource and has mechanical properties similar to those of timber. Interest in bamboo for construction continues to grow as industry focus shifts toward reducing the environmental impact and embodied energy of the built environment. However, raw bamboo cannot meet the engineering requirements of modern buildings due to significant variation in mechanical properties and in geometric size and shape. Additionally, the highly anisotropic nature of bamboo, having markedly different properties in the longitudinal, radial and transversal directions make a unified design paradigm difficult to attain. Finally, bamboo's round hollow shape make connections more complex. Engineered bamboo composites, however, take advantage of the excellent fundamental material properties of bamboo while providing a uniform distribution of these as well as regular shapes, more attractive to the construction industry. Such sustainable alternatives have been developed for structural applications in recent years (Huang et al. 2013).

Two examples of engineered bamboo are laminated bamboo and bamboo 'scrimber'. Laminated bamboo consists of neatly arranged slender bamboo strips joined with adhesive. The bamboo culm is split, planed, processed (bleached or caramelised), laminated and pressed to form the board product (Fig. 1a, b). In contrast, bamboo

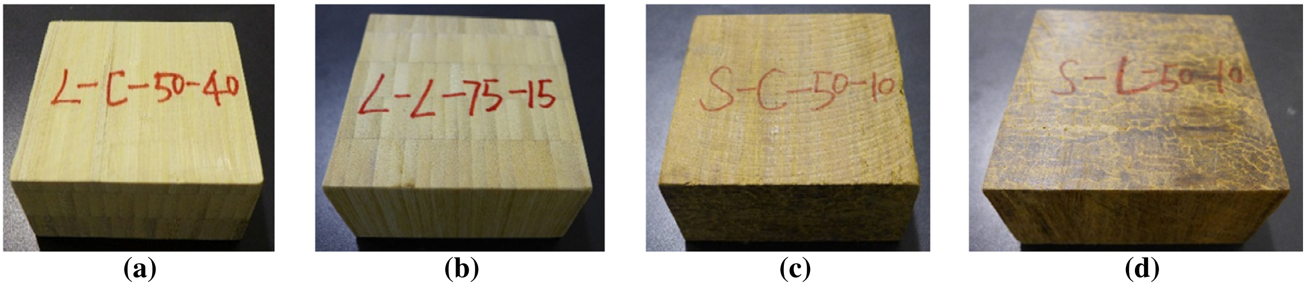


Fig. 1 Sample grain configurations. **a** Laminated bamboo (across the grain). **b** Laminated bamboo (along the grain). **c** Bamboo scrimber (across the grain). **d** Bamboo scrimber (along the grain)

scrimber, also referred to as strand woven or parallel strand bamboo (PSB), is made of crushed fibre bundles saturated in resin and compressed into a dense block (Fig. 1c, d). The process maintains the longitudinal direction of the bamboo fibres and utilises the resin matrix to connect the fibre bundles. The manufacturing process of both engineered bamboo products was illustrated in detail by Sharma et al. (2015a, b). To explore the applicability and facilitate the use of these engineered bamboo products in structural applications, their mechanical properties have been carefully studied (Sharma et al. 2015b). Sinha et al. (2014) and Huang et al. (2013) also reported on laminated bamboo and scrimber properties, respectively, comparable or superior to those of many timber and timber-based products thereby demonstrating the good potential of these materials for structural framing.

Bamboo, however, like other combustible materials, provides fuel to a building fire while simultaneously losing structural load carrying capacity as the bamboo is consumed. When burned, bamboo produces heat, smoke and toxic gases which affect both occupant casualty and property loss. Thus the study of the combustion properties of engineered bamboo is critical to the safety of bamboo building construction. When exposed to fire, a charring layer develops on the surface of engineered bamboo members. Although this charring layer does not contribute to the residual capacity of the member, it protects the interior of the bamboo cross-section from heat and, because the thermal conductivity of the charring layer is much lower than that of the unburnt bamboo, reduces the amount of heat transferred by the surface burning to the unburnt part of the bamboo section.

The reduced cross-section method (EN1995-1-2 2004), which is based on the expected charring depth, is often used to calculate the residual capacity of timber members in and following fire events. This method can also be applied to engineered bamboo members. Thus, the prediction of charring depth or charring rate is crucial to the safe design for fire of bamboo structures. Mena et al. (2012) experimentally studied the fire ignition and flame spread using a LIFT device (Lateral Ignition and Flame Spread Test) and charring rate of both round and laminated *Guadua angustifolia kunth* (*Guadua*) bamboo using an electric muffle furnace. The fire performance of bamboo was also compared to that of plywood. The measured charring rate of round *Guadua* and laminated *Guadua* were found to be 0.24 and 0.59 mm/min, respectively. In most measured parameters, *Guadua* exhibited better results than plywood, and most were comparable to those commonly indicated for different wood species. It is noted that the charring rate obtained from a muffle furnace is different from that described in Eurocode 5, which was developed for a full-scale room fire.

Few studies of the fire performance of laminated bamboo or bamboo scrimber are available in the literature. However, a large number of studies report on the fire performance of timber providing reference and bases of comparison for the study of engineered bamboo. Cone calorimeter tests are typically used to measure the combustion characteristics of timber exposed to constant external heat flux. The test results from cone calorimeter tests have been shown to correlate with results from full-scale room fires (Chung 2010; Grexa and Lubke 2001; Lee et al. 2011; Spearpoint and Quintiere 2001). Compared to full-scale tests, cone calorimeter tests are a convenient and less-expensive means of obtaining charring properties of timber (White and Tran 1996), treated lumber and engineered wood products.

In this context, this paper presents a study aimed at the evaluation of the combustion and charring performance of two types of engineering bamboo products using cone calorimeter tests. The experimental results were compared with the performance of typical softwoods and hardwoods.

2 Materials and methods

In this study, the cone calorimeter test was employed to investigate the combustion and charring properties of laminated bamboo sheets and bamboo scrimber. The ignitability and combustibility parameters were calculated (Spearpoint and Quintiere 2001) and the time to ignition, heat release and mass loss rates, specific extinction area, effective heat of combustion, and carbon monoxide (CO) and carbon dioxide (CO_2) yield of the four cases were compared. The measured charring rates from the cone calorimeter tests at a heat flux of 50 kW/m^2 and exposure time of 30–60 min were taken as equivalent to those obtained from standard furnace tests (Tsantaridis and Ostman 1998). Results were compared with those promulgated in existing design guidelines for wood (AS1720.4 2006; EN1995-1-2 2004). In this manner the fire performance of these bamboo products were compared and summarized, providing reference for fire protection measurement for bamboo structures and furnishings. This study also demonstrates the utility of the relative simple-to-conduct cone calorimeter test, particularly for obtaining charring data.

2.1 Test materials, specimens and matrix

Two types of commercially available engineered bamboo products were tested in this study: laminated bamboo sheets and bamboo scrimber. Both of these products are manufactured from Moso bamboo strips with polyurethane adhesive. The adhesive was applied with a glue proportion (final product dimensions) of approximately 150 g/m^2 for the laminated bamboo sheets and 168 kg/m^3 for the bamboo scrimber. Material properties for these materials are reported in Table 1. Specimens were cut as shown in Fig. 1 such that the grain was perpendicular (i.e., across the grain) or parallel (i.e., along the grain) to the incident heat flux. All specimens were 100 × 100 × 50 mm^3 (1 mm tolerance). Tests were conducted at three different levels of constant incident heat flux: 25, 50, and 75 kW/m^2. At each level of incident heat flux, samples were heated for 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 min, respectively. One sample was tested at each heating time. The different heating times allowed the simultaneous measurement of combustion and charring properties. In many cases, particularly when the incident heat flux is 75 kW/m^2, samples were completely burned after 30 to 55 min heating; thus longer durations were not tested. Table 2 (rows 1–3) lists the specimen density (ISO13061-2 2014) and moisture content (ISO13061-1 2014).

2.2 Cone calorimeter tests

A cone calorimeter was employed to evaluate the combustion properties of the specimens according to ISO5660-1:2002 (ISO5660-1 2002). The cone calorimeter allows quantitative collection of time to ignition, heat release rate, mass loss rate and smoke gases including CO and CO_2. In a cone calorimeter test, heat release rate is determined based on the oxygen depletion principle, utilising the fact that heat release per unit mass of oxygen consumed is approximately independent of the type of fuel, having a value of 13.1 MJ/kg with an error of 5 %. This value is obtained from cone calorimeter tests as follows (ISO5660-1 2002):

$$\dot{q}''(t) = \frac{\dot{q}(t)}{A} = \frac{1.1c}{A}\frac{\Delta H_c}{r_0}\sqrt{\frac{\Delta P}{T_e}}\left[\frac{X^0_{O_2} - X_{O_2}(t)}{1.105 - 1.5X_{O_2}(t)}\right] \quad (1)$$

where $\dot{q}(t)$ is the heat release rate (kW); A is the initially exposed area (m^2); ΔH_c is the net heat of combustion (kJ/kg); 1:10 is the ratio of oxygen to air molecular weights, and r_o is the stoichiometric oxygen/fuel mass ratio; ΔP is orifice meter pressure differential; T_e is absolute temperature of gas at the orifice meter; $X_{O2}(t)$ is oxygen analyser reading, mole fraction of oxygen and $X^0_{O_2}$ is initial value of oxygen analyser reading.

The yield of combustion gases was measured with a CO and CO_2 analyser. Smoke production was analysed by measuring how the smoke attenuates a laser beam in the exhaust duct. The attenuation is related to volume flow, resulting in a measure of smoke density called smoke extinction area having units of m^2/s. The ranges of the

Table 1 Material properties of laminated bamboo and scrimber

Bamboo volume ratio	Laminated bamboo		Bamboo scrimber	
	Parallel –	Perpendicular	Parallel $V_f = 0.915$	Perpendicular
Tensile strength/MPa (Sharma et al. 2015a)	$f_{t\|} = 90$	$f_{t\perp} = 2$	$f_{t\|} = 120$	$f_{t\perp} = 3$
Tensile modulus/GPa (Huang et al. 2013)			$E_{t\|} = 10$	$E_{t\perp} = 31$
Compressive strength/MPa (Sharma et al. 2015a)	$f_{c\|} = 77$	$f_{c\perp} = 22$	$f_{c\|} = 86$	$f_{c\perp} = 37$
Compressive modulus/GPa (Huang et al. 2013)	–	–	$E_{c\|} = 12$	$E_{c\perp} = 14$
Modulus of rupture/MPa (Sharma et al. 2015a)	$f_{b\|} = 77–83$	–	$f_{b\|} = 119$	–
Flexural modulus/GPa (Sharma et al. 2015a)	$E_{b\|} = 11–13$	–	$E_{b\|} = 13$	–

Table 2 Measured combustion and charring properties

Row	Types		Laminated bamboo						Bamboo Scrimber						Douglas Fir (Xu et al. 2015)	Merbau (Xu et al. 2015)
	Orientation		Across grain			Along grain			Across grain			Along grain			Softwood	Hardwood
	Calorimeter heat flux	kW/m^2	25	50	75	25	50	75	25	50	75	25	50	75	50	50
1	Density	kg/m^3	677	677	677	677	677	677	1071	1071	1071	1071	1071	1071	470	860
2	Moisture content (MC)	%	10.5	10.5	10.5	10.5	10.5	10.5	10.9	10.9	10.9	10.9	10.9	10.9	14.0	19.5
3	Density @ MC = 12 %	kg/m^3	687	687	687	687	687	687	1083	1083	1083	1083	1083	1083	460	800
4	Time to ignition	s	132	18	9	147	28	12	189	33	15	313	59	23	23	148
5	Critical heat flux	kW/m^2	6	6	6	7	7	7	7	7	7	8	8	8	18	40
6	Ignition temperature	°C	297	297	297	320	320	320	320	320	320	340	340	340	478	643
7	Thermal response parameter	$kW\ s^{1/2}/m^2$	235	235	235	269	269	269	297	297	297	376	376	376	182	275
8	First peak heat release rate	kW/m^2	183	235	311	162	239	304	220	231	282	139	204	273	151	110
9	Time at first peak heat release	s	130	40	28	175	52	31	204	56	32	355	82	46	55	248
10	Average heat release rate in 5 min	kW/m^2	91	135	168	72	121	148	75	118	152	48	116	144	61	30
11	Specific extinction area	m^2/kg	−5	1	43	2	−3	27	0	2	26	−1	−5	15	2	9
12	Effective heat of combustion	MJ/kg	11	13	12	8	11	11	9	11	11	7	11	10	10	4
13	CO yield	g/kg	23	8	7	78	8	7	58	9	8	76	9	8	Not reported	Not reported
14	CO_2 yield	g/kg	960	1019	981	688	950	936	722	923	861	553	849	842	862	390
15	Measured char depth (mm) at…	5 min	4	5	7	4	11	7	2	5	5	2	4	5	11	6
		10 min	7	9	13	7	14	14	5	6	9	5	7	10	15	6
		15 min	11	13	17	10	19	19	6	9	11	8	13	14	19	9
		20 min	14	16	22	12	19	22	8	12	13	10	14	16	23	8
		25 min	17	22	25	15	24	25	10	15	17	10	16	19	26	11
		30 min	20	25	29	16	27	29	11	16	20	14	19	22	32	14
		35 min	23	28	35	18	29	41	12	16	22	15	22	23	39	16
		40 min	23	30	41	20	31	–	14	17	25	16	21	28	46	19
		45 min	23	33	49	23	36	–	14	19	26	18	29	31	–	17
		50 min	25	35	–	25	39	–	15	21	28	18	28	37	–	18
		55 min	27	41	–	28	41	–	15	24	29	20	29	42	–	19
		60 min	29	–	–	30	48	–	17	25	35	21	33	50	–	22
16	Average char rate (30–60 min)	mm/min		0.76			0.76			0.44			0.58		1.11	0.41
17	EC 5 (EN1995-1-2 2004) predicted char rate	mm/min	0.65 (softwood)			0.65 (softwood)			0.50 (hardwood)			0.50 (hardwood)			0.65	0.50
18	AS1720.4 (2006) predicted char rate	mm/min	0.57			0.57			0.47			0.47			0.77	0.52

'–' no charring specimen tested

paramagnetic oxygen analyser, CO analyser and CO_2 analyser were 0–25, 0–10 and 0–1 %, respectively.

All test specimens were exposed in their horizontal orientation with the standard pilot ignitor operating. All sides except the top side of specimens were wrapped with 0.03–0.05 mm thick aluminium foil. Specimens were placed in the same holder and exposed to a cylindrical heater located 25 mm from the top surface of the specimen, where the value of heat flux was calibrated.

During the heating process, the imposed heat flux was kept constant (25, 50 or 75 kW/m^2). Flammable gas produced when the bamboo was heated was ignited with the spark ignitor. The fibrous material in the bamboo is combustible and with the burning of the specimens, the charring depth gradually increases. After the designated heating time (5–60 min), plasterboard was placed above the specimen to extinguish the specimen. To avoid the influence of smoulder on the charring depth, specimens were extinguished with water. Specimens were then cut into half along their central line, and the residual height at third points was measured. The difference of the original height (50 mm) and the average residual height was recorded as the charring depth.

3 Results and discussion

During the cone calorimeter tests, the following parameters were recorded: time to ignition, heat release rate, peak heat release rate, smoke production rate, carbon monoxide yield and carbon dioxide yield. Following each test, the charring depth was recorded. A summary of all test results is provided in Table 2 and a discussion of each is provided in the following sections.

3.1 Combustion properties

3.1.1 Time to ignition

The time to ignition (t_{ign}) is the time required to establish sustained flaming on the sample surface due to heat radiation and is an important factor for evaluating the burning behaviour of materials. A material with a shorter time to ignition is more flammable. In all but one case, ignition was observed in less than 5 min. The t_{ign} values reported in Table 2 (row 4) are the average values obtained over all specimens tested at a given heat flux. The coefficients of variation of t_{ign} values were below 0.2 for all cases. At a heat flux of 25 kW/m^2, the laminated bamboo with the grain perpendicular to the incident heat flux was observed to be the most flammable, exhibiting $t_{ign} = 132$ s while, the bamboo scrimber with the grain parallel to the incident heat flux was the least flammable, having $t_{ign} = 313$ s. At 50 and 75 kW/m^2 all specimens exhibited similar behaviour with times to ignition of 18–59 and 9–23 s, respectively.

As illustrated in Fig. 2, the inverse of the square root of time to ignition ($t_{ign}^{-1/2}$) is proportional to the imposed heat flux, which indicates that the materials in this study are thermally thick (Delichatsios 1999). For thermally thick conditions, time to ignition is given by (Delichatsios 1999):

$$\frac{1}{\sqrt{t_{ign}}} = \frac{2}{\sqrt{\pi}} \frac{\dot{q}'' - 0.64\dot{q}''_{cr}}{\sqrt{k\rho c}\left(T_{ign} - T_0\right)} \quad \cdot \dot{q}'' > 2\dot{q}''_{cr} \tag{2a}$$

$$\frac{1}{\sqrt{t_{ign}}} = \frac{\pi}{\sqrt{\pi}} \frac{\dot{q}'' - \dot{q}''_{cr}}{\sqrt{k\rho c}\left(T_{ign} - T_0\right)} \quad \cdot \dot{q}'' < 1.2\dot{q}''_{cr} \tag{2b}$$

where t_{ign} is the time to ignition; $\dot{q}''$ is the rate of heat release per unit area (kW/m^2); k is the thermal conductivity (W/m.K); ρ is the density (kg/m^3); c is the specific heat (J/kg.K); T_{ign} is the ignition temperature (K); and T_0 is the initial sample temperature (K). The term $\sqrt{k\rho c}\left(T_{ign} - T_0\right)$ is referred to as the thermal response parameter (TRP) and is an indicator of the ignition resistance of a material.

The critical heat flux and the thermal response parameter can also be calculated from the plot of $t_{ign}^{-1/2}$ versus heat flux (Delichatsios 1999; Fateh et al. 2014; Spearpoint and Quintiere 2001). The critical heat flux is the lowest incident heat flux where ignition occurred. It is an indicator of the possibility of ignition. One way to obtain the critical heat flux is to expose successive samples to decreasing incident heat fluxes until ignition no longer occurs. This approach can be time-consuming and may require several tests to find the bounds of critical heat flux depending on the resolution required. Alternatively, the critical heat flux, $\dot{q}''_{cr}$, can be estimated from the $t_{ign}^{-1/2}$ versus heat flux plot as (Spearpoint and Quintiere 2001)

$$\dot{q}''_{cr} = (\dot{q}'')_{\text{intercept}}/0.76 \tag{3}$$

where $(\dot{q}'')_{\text{intercept}}$ is the intercept with the abscissa of a straight line fit though the plot of $t_{ign}^{-1/2}$ versus incident heat flux (kW/m^2) as shown in Fig. 2.

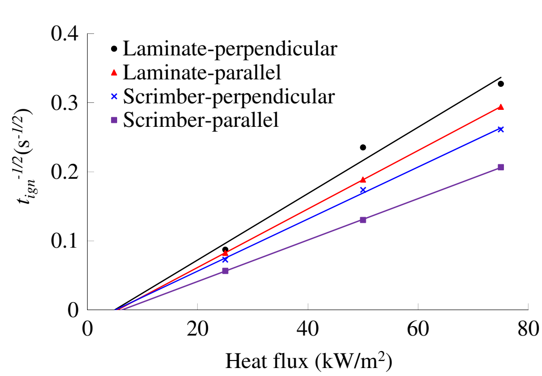


Fig. 2 $t_{ign}^{-1/2}$ versus heat flux curves

The ignition temperature, T_{ign}, can be approximated from Eq. 4, assuming that all heat losses from the exposed surface are expressed as radiation heat losses which are dominant in the present case because the ignition temperature is around 600 K (Spearpoint and Quintiere 2001).

$$T_{ign} \approx \left(\frac{\dot{q}''_{cr}}{\sigma} \right)^{1/4} \tag{4}$$

In which $\sigma = 5.67 \times 10^{-8}$ W/(m^{2}K^4) is the Stefan-Boltzmann radiation constant.

Table 2 (rows 5 through 7, respectively) presents the calculated values of critical heat flux (Eq. 3), ignition temperature (Eq. 4) and thermal response parameter (TRP). All cases show similar values of critical heat flux. The observed ignition temperature for the laminated bamboo with the grain parallel to the incident heat flux and the bamboo scrimber with the grain perpendicular to the incident heat flux were comparable, while those observed for the laminated bamboo with the grain perpendicular to the incident heat flux were slightly reduced and those of bamboo scrimber with the grain parallel to the incident heat flux were increased. In terms of the thermal response parameter, the bamboo scrimber with the grain parallel to the incident heat flux exhibited the highest value and the laminated bamboo with the grain perpendicular to the incident heat flux has the lowest. Once again, by any measure, the laminated bamboo with the grain perpendicular to the incident heat flux is the most flammable of the cases considered, the laminated bamboo with the grain parallel to the incident heat flux and the bamboo scrimber with the grain perpendicular to the incident heat flux are similar, the bamboo scrimber with the grain parallel to the incident heat flux is less flammable than these.

3.1.2 Heat release rate

Heat release rate, $\dot{q}''$, which is defined as heat release per unit area for samples under a constant imposed heat flux, is the most important input parameter required in zone and field models since it controls the characteristic of the fire and indicates the contribution to the development of a fire. Figure 3 compares the measured heat release rates of different bamboo products under three imposed heat fluxes. In all curves, it is observed that the heat release rate increased suddenly when the specimen was ignited and then dropped and remained relatively constant for the duration of the test. The heat release rate was observed to increase before the end of test for some cases at heat flux levels of 50 and 75 kW/m^2. Two peaks are commonly reported during burning tests of timber: the peak at the initial stage of burning and a second peak before flame out (Chung 2010; Grexa and Lubke 2001; Kim et al. 2011; Lee et al. 2011). The initial peak is mostly due to the formation of the charring layer which decreases the amount of heat and emission of gas into the burning area. After the occurrence of the first peak, the heat release rate tends to become stable. The second increase of heat release rate started because of the heat accumulated at the back of the sample.

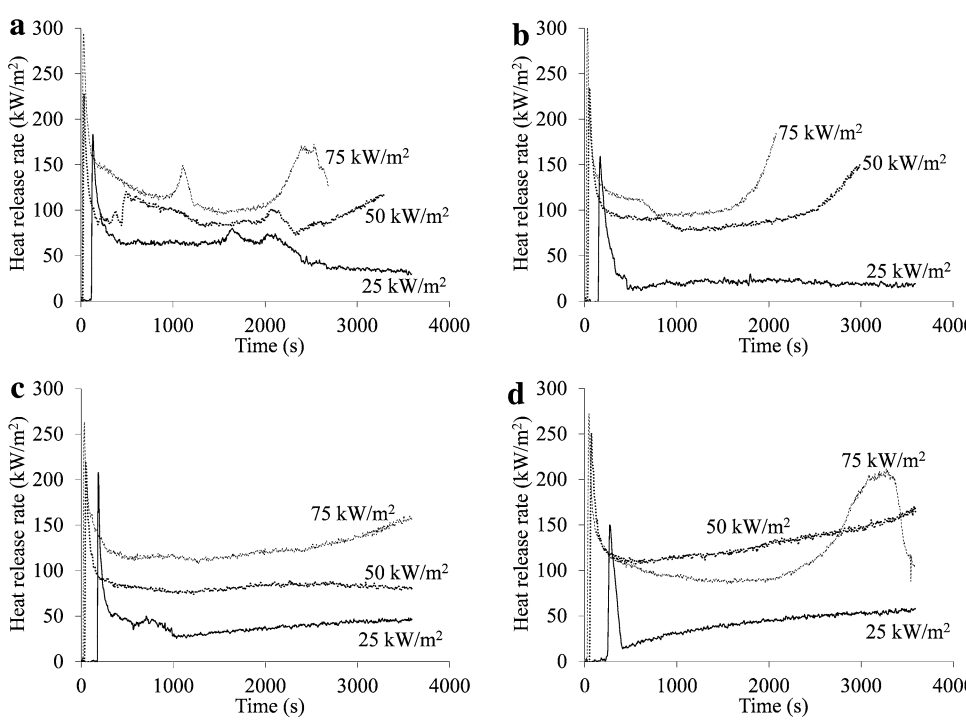


Fig. 3 Variation of heat release rate with time (only *curves* having longest exposure time are shown). **a** Laminated bamboo (*perpendicular* to grain), **b** laminated bamboo (*parallel* to grain), **c** bamboo scrimber (*perpendicular* to grain) and **d** bamboo scrimber (*parallel* to grain)

The second peak is evident in some of the curves reported in Fig. 3. Because of the simultaneous charring study, samples were not completely burned and thus the second peak was typically not reached.

The average heat release rate over the 5 min following ignition can be used to predict the time to flashover in an ISO 9705 room corner test (Hansen and Hovde 2002). Table 2 (rows 8 through 10, respectively) lists the peak heat release rate and corresponding time and the average heat release rate over the 5 min following ignition. The peak heat release time follows the time to ignition, in all but one case, occurring in less than 5 min.

As seen in Table 2, the peak and average heat release rates increased with increasing heat flux while the time to the initial peak decreased. The observed heat release rates for the laminated bamboo with the grain perpendicular and parallel to the incident heat flux and the bamboo scrimber with the grain perpendicular to the incident heat flux were comparable, while those observed for the bamboo scrimber with the grain parallel to the incident heat flux were slightly reduced.

3.1.3 Mass loss rate

Mass loss rate is the rate of change of sample mass during the burning process, which is calculated using five-point numerical differentiation equations in cone calorimeter tests (ISO5660-1 2002). Mass loss rate shows the level of pyrolysis, volatilization, and burning of samples under constant heat flux. The mass loss rate is closely related with the heat release rate, specific extinction area, and CO yield. A lower mass loss rate is indicative of a lower propensity for flame spread. The mass loss rate is also a useful parameter in post-fire forensic investigations. Figure 4 illustrates the evolution of mass loss rate with time for the two engineered bamboo products with the grain perpendicular and parallel to the incident heat flux. Similar to the heat release rate, the mass loss rate increased sharply when the specimen ignited, decreased gradually thereafter eventually became constant at a near-zero rate. The mass loss rate increased with increasing heat flux and was observed to be slightly greater for bamboo scrimber, compared to the laminated bamboo tested. The final observation is believed to be indicative of the relatively high resin content in the scrimber (Table 1).

3.1.4 Specific extinction area

Specific extinction area is defined as the ratio of the extinction area of smoke to the mass loss of the specimen associated with the production of that smoke (ISO5660-1 2002). This value indicates the smoke production capacity of a unit mass of combustible material during the pyrolysis and volatilization process and is an important index for smoke production in a fire hazard. Table 2 (row 11) gives the specific extinction areas for all specimens. While the laminated bamboo with the grain perpendicular to incident heat flux exhibited notably higher values, the specific extinction areas of the other three cases were relatively similar.

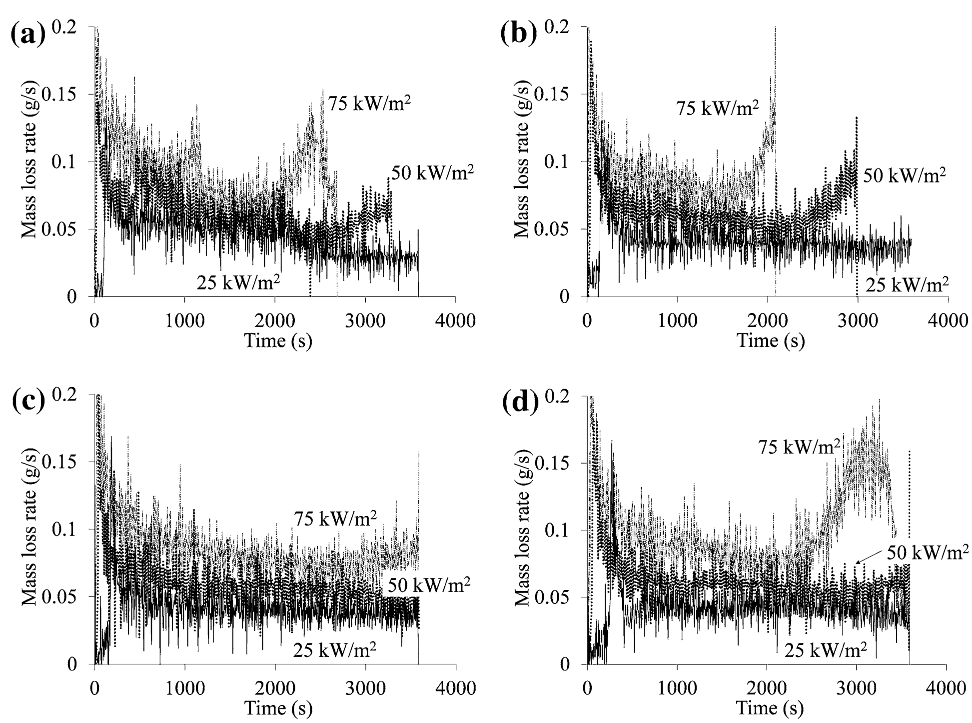


Fig. 4 Variation of mass loss rate with time (only *curves* having longest exposure time are shown). **a** Laminated bamboo (*perpendicular* to grain), **b** laminated bamboo (*parallel* to grain), **c** bamboo scrimber (*perpendicular* to grain), and **d** bamboo scrimber (*parallel* to grain)

3.1.5 Effective heat of combustion

The effective heat of combustion is the energy generated by combustion reactions per unit mass of sample, and is calculated as the ratio of the total heat release rate to the mass loss (ISO5660-1 2002). This value indicates the burning intensity of the volatile compounds in the flame and is helpful in the study of fire retardant. The values of effective heat of combustion are given in Table 2 (row 12). This value increased marginally with increasing heat flux. However, specimens exposed to 25 kW/m^2 heat flux had relatively lower values of effective heat of combustion and higher values of CO yield when compared to other specimens, indicating incomplete combustion of specimens at low level of heat flux.

3.1.6 Carbon monoxide (CO) yield

For bamboo material, the toxic gas produced during burning is mainly CO. The CO yield in the cone calorimeter test was recorded with the CO analyser. In this study, only trace amounts of CO were observed in all the tests as given in Table 2 (row 13). The CO yield decreased with the heat flux.

3.1.7 Carbon dioxide (CO_2) yield

The production of CO_2 in a fire is a significant factor affecting casualty. The CO_2 primarily causes oxygen deficiency and is a respiratory irritant, which, taken together can lead to excessive inhalation of other toxic gases. The CO_2 yield recorded in all tests is given in Table 2 (row 14). All values are similar.

3.1.8 Charring behaviour

For most specimens, smoke decreased sharply and flame expanded immediately at the time of ignition (Fig. 5b). A large flame lasted about 100–200 s (Fig. 5c), and then degraded gradually to an essentially steady state (Fig. 5d). At a heat flux of 25 kW/m^2, specimens ignited within 5 min with the exception of bamboo scrimber with the grain parallel to the incident heat flux (Fig. 5b), and the flame burned for about 400–2500 s (Fig. 5d). At heat fluxes of 50 and 75 kW/m^2, all specimens were ignited, and the flame lasted to the end of the 60 min (3600 s) test. The charring layers for all specimens are shown in Fig. 6.

Fig. 6 Typical observed charring. **a** Laminated bamboo (*perpendicular* to grain) at 25 kW/m^2, **b** laminated bamboo (*perpendicular* to grain) at 50 kW/m^2, **c** laminated bamboo (*perpendicular* to grain) at 75 kW/m^2, **d** laminated bamboo (*parallel* to grain) at 25 kW/m^2, **e** laminated bamboo (*parallel* to grain) at 50 kW/m^2, **f** laminated bamboo (*parallel* to grain) at 75 kW/m^2, **g** bamboo scrimber (*perpendicular* to grain) at 25 kW/m^2, **h** bamboo scrimber (*perpendicular* to grain) at 50 kW/m^2, **i** bamboo scrimber (*perpendicular* to grain) at 75 kW/m^2, **j** bamboo scrimber (*parallel* to grain) at 25 kW/m^2, **k** bamboo scrimber (*parallel* to grain) at 50 kW/m^2, **l** bamboo scrimber (*parallel* to grain) at 75 kW/m^2 ▶

3.1.9 Charring depth

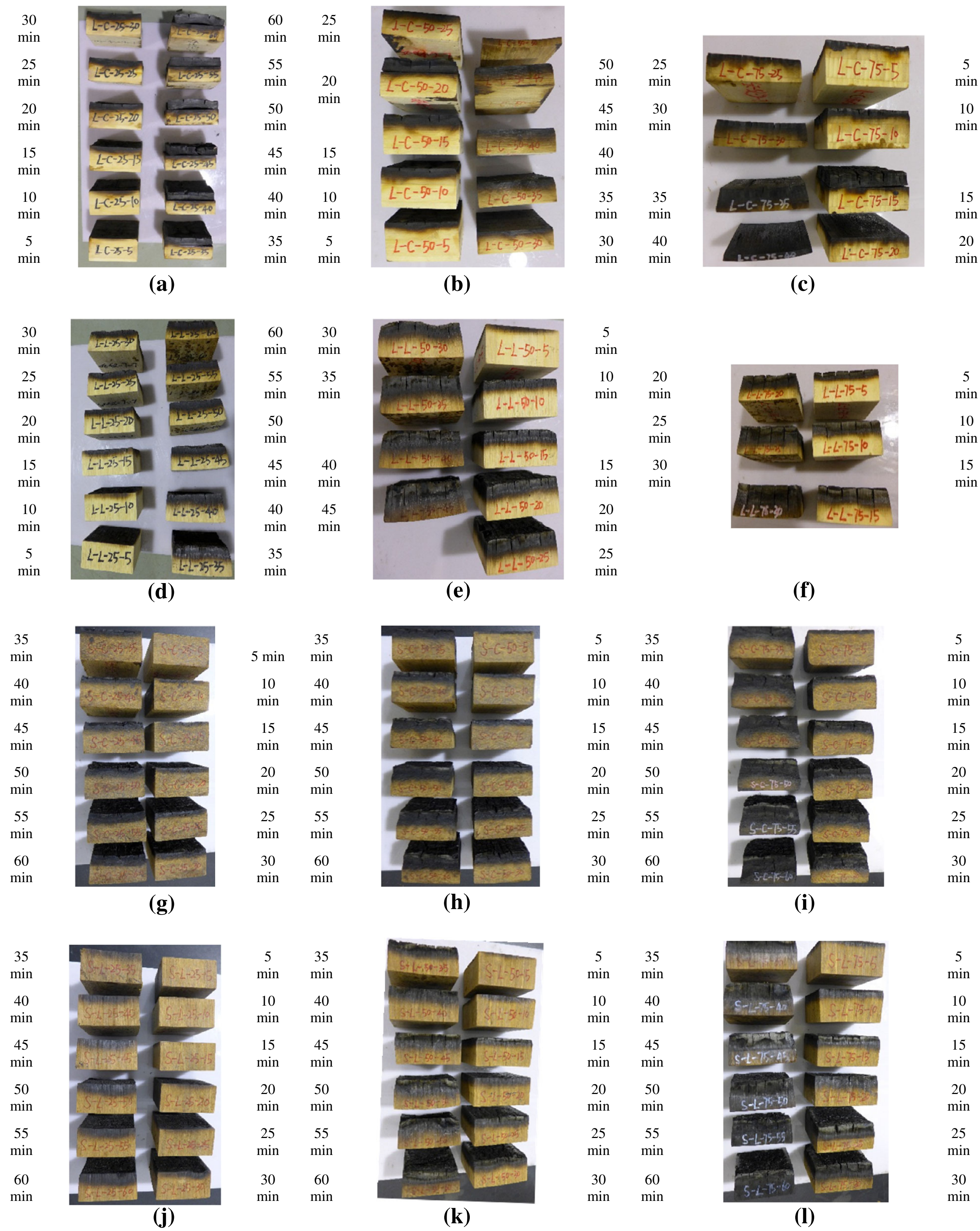
Table 2 (row 15) lists the measured charring depths for all specimens. Charring depth increased with increasing heat flux and exposure time. Figure 7 illustrates the development of charring depth of different cases under the same heat flux with fire exposure time. As seen in Fig. 7, the charring depth is approximately linear with exposure time, as observed by others (White and Tran 1996). Additionally, the observed charring depths for bamboo scrimber are much smaller than those for laminated bamboo.

3.1.10 Charring rate

The average charring rate calculated as the charring depth divided by the fire exposure time observed for each case is shown in Fig. 8. The charring rate was generally observed to increase with heat flux, and decrease with fire exposure time. This behaviour can be explained by the fact that the charring layer formed at the initial stage of burning has a much lower thermal conductivity than unburnt bamboo, which decreases the heat transferred from the specimen surface to the internal bamboo. The formation of the charring layer also stops the reaction between the internal pyrolysis gas and the surrounding air, which prevents the

(a) (b) (c) (d)

Fig. 5 Cone calorimeter test observations. **a** Initial heating. **b** Ignition. **c** Post-ignition large flames (100–200 s). **d** Gradual burn to end of test


30 min 25 min 20 min 15 min 10 min 5 min
60 min 55 min 50 min 45 min 40 min 35 min
(a)
25 min 20 min 15 min 10 min 5 min
50 min 45 min 40 min 35 min 30 min
(b)
25 min 30 min 35 min 40 min
5 min 10 min 15 min 20 min
(c)
30 min 25 min 20 min 15 min 10 min 5 min
60 min 55 min 50 min 45 min 40 min 35 min
(d)
30 min 35 min 40 min 45 min
5 min 10 min 15 min 20 min 25 min
(e)
20 min 25 min 30 min
5 min 10 min 15 min
(f)
35 min 40 min 45 min 50 min 55 min 60 min
5 min 10 min 15 min 20 min 25 min 30 min
(g)
35 min 40 min 45 min 50 min 55 min 60 min
5 min 10 min 15 min 20 min 25 min 30 min
(h)
35 min 40 min 45 min 50 min 55 min 60 min
5 min 10 min 15 min 20 min 25 min 30 min
(i)
35 min 40 min 45 min 50 min 55 min 60 min
5 min 10 min 15 min 20 min 25 min 30 min
(j)
35 min 40 min 45 min 50 min 55 min 60 min
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(k)
35 min 40 min 45 min 50 min 55 min 60 min
5 min 10 min 15 min 20 min 25 min 30 min
(l)

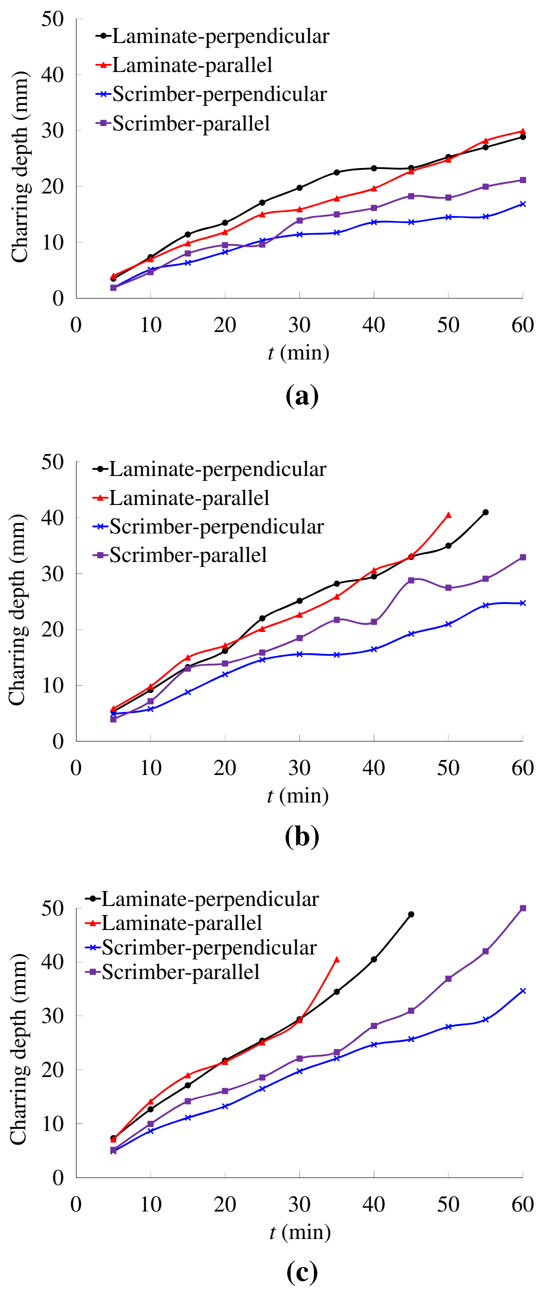

Fig. 7 Observed charring depths. **a** 25 kW/m^2, **b** 50 kW/m^2, **c** 75 kW/m^2

spread of the fire. The charring rate tended to be essentially constant when the fire exposure time exceeded 30 min. Once again, the observed charring rates for bamboo scrimber are smaller than those for laminated bamboo.

In the cone calorimeter tests, the imposed heat flux is constant for the duration of the test. However, in a fire test of bamboo members, the air temperature in the fire compartment is assumed to follow the ISO 834 (ISO834-1 1999) or ASTM 119 (ASTME119-14 2014) standard fire curves, where the heat flux increases with the fire exposure time. At the initial stage of heating, the heat flux is low; after 40 min, the heat flux increases to about 90 kW/m^2.

It was proposed that the charring depths obtained in cone calorimeter tests at 50 kW/m^2 are similar to those obtained in furnace tests having a duration of 30–40 min for wood (Tsantaridis and Ostman 1998). Additionally, it is observed (Fig. 8) that the charring rate tends to be relatively constant when the fire exposure time exceeds 30 min. Thus, similar to timber, the average charring rate for specimens exposed to a heat flux of 50 kW/m^2 for 30–60 min are proposed to be representative for use in fire design for engineered bamboo; these average values are reported in Table 2 (row 16). As correlations are not available for bamboo, the recommendations for predicted charring rate of wood promulgated by EC-5 (EN1995-1-2 2004) and Australian standard AS1720.4 (2006) are shown in Table 2 (rows 17 and 18, respectively) for comparison. The EC-5-prescribed charring rate of softwood having density greater than 290 kg/m^3 is a constant rate of 0.65 mm/min while that for hardwood having density greater than 450 kg/m^3 is 0.50 mm/min. As seen in Table 2 (rows 16–17), the value for hardwood reflects the performance of bamboo scrimber relatively well while the value for softwood underestimates the charring rate for laminated bamboo. In the Australian standard, the charring rate is defined as being inversely proportional to the square of timber density and does not distinguish between softwood and hardwood:

$$\beta = 0.4 + \left(\frac{280}{\rho}\right)^2 \tag{5}$$

where β is the charring rate, and ρ is density. To exclude the influence of the moisture content, the density is defined when the moisture content is 12 % (see Table 2, row 3). The AS 1720.4 predictions also underestimate the observed average charring rates for the laminated bamboo but are reasonably predictive of the bamboo scrimber (Table 2, rows 16 and 18).

3.2 Comparison with typical timber results and relative performance of specimens

As a basis for comparison, fire performance of representative softwood (Douglas fir) and hardwood (Merbau) obtained in a similar way and using cone calorimeter instrument as used for the present study are also reported in Table 2 (Xu et al. 2015).

Table 3 summarises the relative performance of the engineered bamboo with different grain orientation and the representative softwood and hardwood performances in terms of the fire performance parameters considered. Bamboo scrimber is more resistant to fire than laminated bamboo and is generally comparable in performance to the

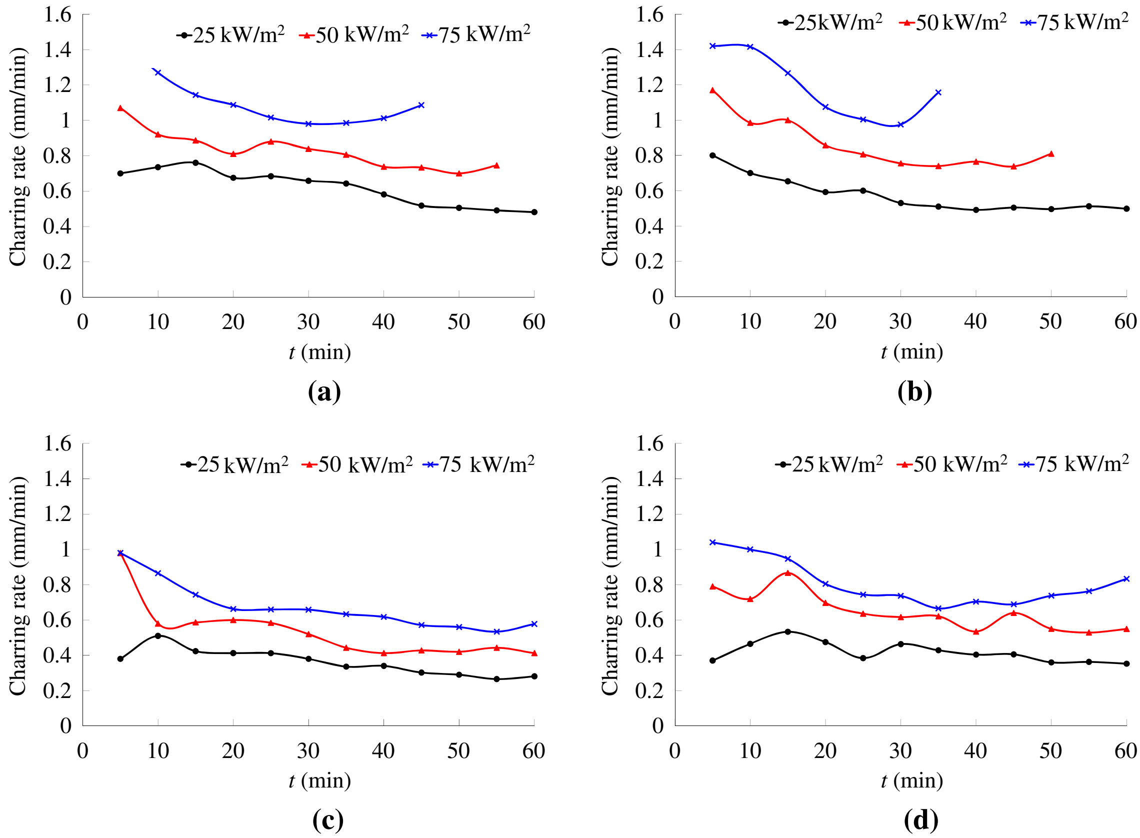

Fig. 8 Observed charring rates. **a** Laminated bamboo (*perpendicular* to grain), **b** laminated bamboo (*parallel* to grain), **c** bamboo scrimber (*perpendicular* to grain), **d** bamboo scrimber (*parallel* to grain)

Table 3 Relative fire performance of five species tested

Performance parameter	Criteria	Performance					
		1 (best)	2	3	4	5	6 (poorest)
Density	Greatest	Scrimber		Hardwood	Laminated		Softwood
Ignition time	Longest	Hardwood	Scrimber ∥	Scrimber ⊥	Laminated ∥	Softwood	Laminated ⊥
Critical heat flux	Greatest	Hardwood	Softwood	Scrimber ∥	Laminated ∥ and scrimber ⊥		Laminated ⊥
Ignition temperature	Greatest	Hardwood	Softwood	Scrimber ∥	Laminated ∥ and scrimber ⊥		Laminated ⊥
Peak heat release rate	Lowest	Hardwood	Softwood	Scrimber ∥	Laminated ∥, scrimber ⊥ and laminated ⊥		
Time to peak heat release rate	Longest	Hardwood	Scrimber ∥	Scrimber ⊥	Softwood	Laminated ∥	Laminated ⊥
Average heat release rate	Lowest	Hardwood	Softwood	Scrimber ∥	Laminated ∥ and scrimber ⊥		Laminated ⊥
Specific extinction area	Lowest	Scrimber ∥	Laminated ∥ and scrimber ⊥		Laminated ⊥	Softwood	Hardwood
Effective heat of combustion	Lowest	Hardwood	Softwood	Laminated ∥, scrimber ⊥ and scrimber ∥			Laminated ⊥
CO yield[a]	Lowest	Laminated ⊥	Scrimber ∥, laminated ∥ and scrimber ⊥				
CO_2 yield	Lowest	Hardwood	Scrimber ∥ and softwood		Laminated ∥ and scrimber ⊥		Laminated ⊥
Charring depth at 30 min	Lowest	Scrimber ⊥ and hardwood		Scrimber ∥	Laminated ∥, and laminated ⊥		Softwood
Average charring rate	Lowest	Hardwood	Scrimber ⊥	Scrimber ∥	Laminated ∥, and laminated ⊥		Softwood

[a] Not reported for softwood or hardwood

typical hardwood (Merbau) and softwood (Douglas fir) reported. Specimens with the grain parallel to the incident heat flux were relatively less flammable than specimens with the grain perpendicular to the incident heat flux for both laminated bamboo and bamboo scrimber. The orientation of the grain had negligible influence on the charring rate for laminated bamboo, while for bamboo scrimber, specimens with the grain parallel to the incident heat flux exhibited a greater charring rate.

The ranking of performance parameters of timber and bamboo products individually correlates with the product density (i.e., scrimber outperforms laminate bamboo and hardwood outperforms softwood), however when compared across products (bamboo and timber), the denser bamboo does not perform better than the comparable timber product. Thus, while correlations derived for timber products on the basis of density may serve as a guide for engineered bamboo, specific test results are needed to calibrate these.

4 Conclusion

The combustion and charring properties of two types of engineered bamboo products for structural applications: laminated bamboo sheets and bamboo scrimber were investigated through cone calorimeter tests conducted at three levels of heat flux, 25, 50 and 75 kW/m^2. The orientation of the grain was either perpendicular or parallel to the incident heat flux. The ignitability and combustibility parameters of these four cases were calculated (Spearpoint and Quintiere 2001) and the time to ignition, heat release and mass loss rates, specific extinction area, effective heat of combustion, and CO and CO_2 yield were compared. Performance was compared with typical softwood and hardwood species (Xu et al. 2015). The following conclusions are drawn:

1. The time to ignition decreased with increasing heat flux. The average heat release rate over the 5 min following ignition, peak heat release rate, mass loss rate, effective heat of combustion increased with increasing heat flux. Among the four cases considered, laminated bamboo with the grain perpendicular to incident heat flux exhibited the shortest time to ignition and the highest specific extinction area, while the bamboo scrimber with the grain parallel to incident heat flux had the longest time to ignition and the lowest specific extinction area. The average and peak heat release rates of the laminated bamboo with the grain perpendicular and parallel to the incident heat flux and the bamboo scrimber with the grain perpendicular to the incident heat flux were comparable, while those observed for the bamboo scrimber with the grain parallel to the incident heat flux were slightly reduced. The mass loss rate was observed to be slightly greater for bamboo scrimber, compared to the laminated bamboo tested. While the laminated bamboo with the grain perpendicular to incident heat flux exhibited notably higher values, the specific extinction areas of the other three cases were relatively similar.
2. Only trace amounts of CO were observed in all the tests. The CO_2 yield of all cases tested exhibited similar values. The measured charring rates from the cone calorimeter tests were transformed to equivalent charring rates for standard furnace tests (Tsantaridis and Ostman 1998) and compared with those promulgated in existing design guidelines (AS1720.4 2006; EN1995-1-2 2004) for softwood. The following conclusions are drawn:
3. The charring depth for all five species was observed to increase with fire exposure time, and with increasing heat flux while the charring rate was observed to increase with heat flux, and decrease with fire exposure time. The charring rate tended to be essentially constant when the fire exposure time exceeded 30 min. The observed charring rates for bamboo scrimber are smaller than those for laminated bamboo.
4. For the laminated bamboo, both the EC-5 and AS 1720.4 predictions underestimate the observed average charring rates, while for bamboo scrimber, the EC-5 hardwood and AS 1720.4 predictions were generally acceptable in the perpendicular orientation and marginally underestimated the observed charring rates when the grain is parallel to the incident heat flux.

In terms of the relative performance of the four cases tested, bamboo scrimber is more resistant to fire reflecting the fact that it is almost twice as dense as laminated bamboo considered. The orientation of the grain has negligible influence on their overall performance. In general, bamboo scrimber did not perform as well as a representative hardwood although it generally performed better than a representative softwood. Laminated bamboo performed similarly to a representative softwood. Finally, this study demonstrates the utility of the relatively inexpensive cone calorimeter test for the rapid assessment of combustion and particularly charring performance of engineered bamboo.

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