Experimental study of performance of engineered bamboo beams exposed to three-sided standard fire

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Abstract: This paper presents a pilot experimental study aimed at evaluating the performance of engineered bamboo beams exposed to and following exposure to three-sided standard fire conditions. Nine tests were carried out including two constant applied load fire tests and seven flexural tests of engineered bamboo beams following exposure to fire. Test parameters include load ratio in fire tests, fire exposure duration, beam geometry and engineered bamboo type. Two engineered bamboo products: laminated bamboo and bamboo scrimber, commonly used in construction were considered. In all cases, regardless of fire exposure, the failure mode was flexural failure associated with tensile fracture of the extreme tension fibre. The stiffness and ultimate loads of engineered bamboo beams were observed to decrease with increased fire time and the strain distribution at the mid-span cross-section remained linear after exposure to the standard fire. The fire resistance of laminated bamboo beams decreased with increased applied load. Charring depth was measured for all beams after tests and equivalent charring rate was calculated. Result shows that laminated bamboo beams had a higher charring rate than the denser bamboo scrimber beams. Both sectional analysis and simplified methods based on the reduced cross-section method are used to determine the fire resistance and ultimate load capacity of the engineered bamboo beams following exposure to fire.

Keywords: engineered bamboo, fire resistance, three-sided standard fire, laminated bamboo, bamboo scrimber.

1. Introduction

Bamboo has been demonstrated to have a number of advantages as a construction material. It is a fast-growing, renewable resource having mechanical properties similar to those of timber. Bamboo is endemic to Latin-America, Asia and East Africa making it well suited to providing a basis for local industry and the development of products driven by the considerations of sustainability and energy savings. Bamboo in its natural form is a cylindrical pole, or culm. Due to its inter- and intra-species variation of geometry and material properties and the need for complex connection forms, full-culm bamboo construction is mostly limited to vernacular and informal construction. Engineered bamboo products, however, take advantage of the excellent material properties of bamboo, mitigating their variation while providing regular shapes, more attractive to the construction industry. Two examples of established engineered bamboo products are laminated bamboo and bamboo scrimber. Laminated bamboo consists of longitudinally arranged slender bamboo strips joined with adhesive. The bamboo culm is split, planed, processed, laminated and pressed to form the laminated bamboo board product. In contrast, bamboo 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. The process maintains the longitudinal orientation of the bamboo fibres and utilises the resin matrix to connect the fibre bundles. The manufacturing process of both engineered bamboo products is described in detail by Sharma et al. [1, 2]. Material properties of engineered bamboo are comparable or superior to those of many timber and timber-based products thereby demonstrating the good potential of these materials for structural framing [3-11].

Bamboo, like other combustible materials, provides fuel to a building fire while simultaneously losing structural load carrying capacity as the bamboo is consumed. Thus the study of the fire performance of engineered bamboo is critical to the safety of bamboo building construction. Mena et al. [12] studied the combustion and charring performance of laminated bamboo board made from *Guadua angustifolia kunth*, and concluded that the laminated bamboo board tested satisfied fire performance as structural and indoor finishing building material. Xu et al. [13] concluded that the combustion and charring performance of *Phyllostachys edulis (Moso)* laminated bamboo and bamboo scrimber were comparable to representative softwood and hardwood performance, respectively. The mechanical properties of *Moso* bamboo scrimber at elevated temperatures was experimentally investigated by Zhong et al. [14] and Xu et al. [15]; numeric models were developed to predict the reduction of mechanical properties at elevated temperatures. Xiao et al. [16] carried out full-scale room fire tests of a light-weight glued-laminated bamboo ('glubam') framed building and concluded that the building was able to survive a fire having a duration exceeding one hour. Most extant studies focus on material performance of engineered bamboo products; few address the structural performance of engineered bamboo members exposed to fire. Equally important in terms of structural safety and the safety of first responders, the post-fire residual capacity of engineered bamboo members is not addressed in the literature. The objective of this paper is to study the fire performance of engineered bamboo beams exposed to, and after exposure to a fire affecting the soffit and sides of the beam; i.e., a three-sided standard fire.

2. Pilot Experimental programme

2.1 Test specimens

In total, nine *P. edulis (Moso)* engineered bamboo beams were prepared and tested. Five laminated bamboo beams all have a cross-section dimensions of 225 mm deep×100 mm wide and have an overall length of 2630 mm. Three bamboo scrimber beams have cross-section dimensions of both 140 mm×100 mm×2430 mm and a fourth is 140 mm×70 mm×2430 mm. These dimensions are commonly available from manufacturers. Experimentally determined material properties of both the laminated bamboo and bamboo scrimber are given in Table 1.

Both engineered materials rely on a binding agent for their performance. The performance of these adhesives, in the case of laminated bamboo, and matrix, in the case of bamboo scrimber, at elevated temperatures is expected to impact the fire performance of the beams. The adhesive used in the laminated bamboo is a polyurethane resin having a glass transition temperature of about 150ºC. The adhesive content of the laminated bamboo is less than 2% of its total mass. The bamboo scrimber, on the other hand, has about 10% resin content by volume. The resin used is also a polyurethane resin having a glass transition temperature of about 150ºC.

2.2 Test program

The test program is outlined in Table 2. All specimens were subject to third-point flexural loading over a simple span of 2400 mm and 2100 mm for laminated bamboo and bamboo scrimber beams respectively (Figure 1). One control specimen of each material (LGB and SGB) was tested to failure in an ambient laboratory environment to establish the capacity of the beams.

Two laminated bamboo and three bamboo scrimber specimens (LGBA and SGBA specimens) were exposed to the initial 10 or 25 minutes of an ISO 834 standard fire [17]. These beams were placed in the furnace (rather than being simply supported) and mineral wool was used to protect the supporting surface and beam ends (Figure 2a). Following fire exposure for the prescribed time (Table 2), the furnace was allowed to cool for about 5 to 7 mins and the beams were moved out the furnace and cooled with water before being tested in flexure in the same manner as the control specimens in order to determine post-fire residual capacity. The top, compression face of the beam was that protected during the fire exposure. Figure 2b shows the beams following fire exposure.

Two additional laminated bamboo specimens (LGB-3 and LGB-4) were loaded with a constant load in third-point flexure over a span of 2400 mm and subjected to the ISO 834 standard fire curve [17] until failure. This test arrangement is shown schematically in Figure 1. The constant loads applied were 35% and 50% of the capacity of the control beam LGB; i.e., 66.5 kN and 95 kN, respectively.

The ISO 834 standard fire curve results in a furnace temperature (in °C) described by $T = 20 + 345\log(8t+1)$, in which t is given in minutes. Thus after 10 and 25 minutes, the furnace temperature was prescribed to be 678 and 815°C, respectively. The furnace and heating conditions met the requirements of *Chinese Standard GB/T 9978.1-*

2008[18], which is similar to ISO 834-1:1999[17]. The measured furnace temperature may differ slightly from the ISO 834 standard fire due to the complex combustion mechanism. However, the error between the measured furnace temperature and the ISO 834 standard fire is within the requirements specified [18]. Additionally, it is acknowledged that although widely used, furnace tests may result in variation of thermal exposure between individual specimens in a furnace and may not be consistent with tests conducted in other furnaces despite meeting ISO 834 requirements.

2.3 Instrumentation

Assuming the temperature field is similar for the beams with the same material and cross section at equal exposed time, multiple thermocouples were installed at two cross sections only in beam LGB-3 and LGB-4 as shown in Figure 3a. The thermocouples were nickel chromium alloy thermocouples, with a temperature range of -200 ^{o}C to 1100 ^{o}C. Two thermocouples were inserted in the same hole to minimize the influence of drilling holes on the thermal and mechanical performance of the beams. The hole was then filled with bamboo dust to exclude the influence of gas within the drilling holes. The temperature distribution in the bamboo scrimber beams was not measured.

Displacement transducers were located at the supports and at mid-span of each beam to monitor the vertical displacements at these locations. For specimens tested at room temperature (all except LBG-3 and LBG-4), strain gauges were installed at mid-span to determine strains through the beam depth as shown in Figure 3b. The charring layer and an assumed thermal pyrolysis zone were removed before the installation of strain gauges on those beams having fire exposure.

3. **Test results and observations**

All flexure test results are summarised in Table 2. Load-deflection curves obtained from the flexure tests are shown in Figure 4 and images of the failed laminated bamboo and bamboo scrimber beams are shown in Figures 5 and 6, respectively.

3.1 Observations from fire exposure

Following 3 to 5 minutes of fire exposure, smoke was observed and increased with time. Photographs of the fire-exposed specimens in Figure 2b show alligator fissures on the exposed beam surfaces and some lamellas of bamboo peeling off the exposed beam soffit.

3.2 Laminated Bamboo flexure tests

Control specimen LGB began to crack at an applied load of 120 kN; this corresponds to the onset of non-linear load-deflection behaviour of the beam (Figure 4a). Crack sounds increased with the increasing load, and at 190 kN, the beam fractured suddenly at the bottom fibre (Figure 5a). For specimen LGBA-1, exposed to fire for 10 minutes, cracking was initially heard at 39 kN. At an applied load of 56 kN, the bottom bamboo lamina fell off and the load-deflection behaviour became distinctly non-linear (Figure 4a). The beam failed at 100.3 kN. Diagonal cracks formed below the left loading points and the bottom fibre fractured at the mid-span as seen in Figure 5b. Specimen LGBA-2, exposed for 25 minutes, exhibited initial cracking at an applied load of 19.1 kN, and at 43.3 kN failed due to the tensile fracture of the lowermost lamina as shown in Figure 5b.

3.3 Bamboo Scrimber flexure tests

Control specimen SGB began to crack at an applied load of 47 kN, indicating the onset of non-linear load-deflection behaviour of the beam (Figure 4b); cracking increased with increasing load. At 52 kN, a crack was observed at the beam soffit at mid-span. The beam failed suddenly at an applied load of 68.1 kN; longitudinal cracks extended to both two loading points (Figure 6a). For specimen SGBA-1, exposed to fire for 10 minutes, cracking was first heard at 38 kN; non-linear load-deflection behaviour began and the beam failed due to tensile fracture of the bottom fibres at 45.5 kN (Figure 6b). Specimen SGBA-2, exposed for 25 minutes, began to crack at an applied load of 14.5 kN, and exhibited a tensile fracture of the bottom fibres at 16.4 kN (Figure 6c). Specimen SGBA-3, having a width of only 70 mm and exposed to fire for 10 minutes began to crack at 14.2 kN. Cracks developed at the bottom of the beam and the beam failed at 22.5 kN (Figure 6d).

3.4 Fire resistance tests

Temperature histories measured from thermocouples embedded in the beams are shown in Figure 7. Displacement time histories of the beams subject to constant load are shown in Figure 8.

About 4 minutes after the fire began, smoke was observed (Figure 9a) and increased with time. In each test, the mid-span deflection, shown in Figure 8, increased gradually with the time, and increased suddenly as the specimens approached failure. Once load carrying capacity was lost, the furnace temperature was cooled and specimens removed and cooled further with water. As shown in Figure 9b, longitudinal and transverse alligator fissures were observed on the side surfaces of the beams and the bottom lamellas of bamboo peeled off due to the charring. More bamboo lamellas were observed to have peeled off near the mid-span.

4. Discussion

4.1 Post-fire flexural behaviour

Load-deflection curves of all specimens are shown in Figure 4. All specimens shown an initially linear phase followed by nonlinear stiffness degradation as the beam approaches failure. As is shown in Figure 4, the effect of fire exposure is to dramatically reduce both the ultimate capacity and stiffness of the beams. The deflection at failure for the laminated bamboo falls with fire exposure although the ultimate deflections of the bamboo scrimber specimens are less effected by fire exposure. Figure 10 shows the development of strain at the top and bottom surfaces of the beams which are consistent with the observations from the load-deflection curves. At the same load levels, the fire-exposed beams exhibit substantially greater extreme fibre strains and the strains increase with fire-exposure duration. Figure 11 shows the strain distribution at the mid-span cross-section of typical engineered bamboo beams tested following fire-exposure. The sections follow the plane-sections assumption, indicating no relative slip (degradation of the adhesive glue lines) between laminates in the laminated bamboo.

Figure 12 summarises the reduction in flexural capacity associated with fire-exposure; the reduction results from a) the decrease of effective cross-section resulting from charring; b) the upward shift of the neutral axis resulting from loss of the lower lamella of the beams; and c) the reduction of strength of the pyrolysis and elevated temperature affected zones due to the heating of bamboo. In this study, the beams were not subject to loading during fire exposure; thus the effects of simultaneous thermal and mechanical loading are neglected. Addition tests fire tests of beams under load are therefore recommended.

4.2 Internal temperature

Figure 7 illustrates the internal temperature development of engineered bamboo beams. Internal beam temperature increased with time and continued to increase after the fire was stopped (at 22 and 10 minutes, respectively in Figures 7a and 7b). The temperature histories indicate a gradient through the cross section and show a plateau at 100ºC corresponding the evaporation of water content. With the exception of thermocouple T4 in LGB-3, internal temperatures did not exceed 150 ºC which is below the glass transition temperature of the adhesive used in these specimens. Thus deterioration of the internal glue lines is not expected. Following testing, it was determined that thermocouple T4 was adjacent to region of local significant charring, explaining the higher temperatures after about 17 minutes of exposure. The fire duration time was relatively short for these specimens; deterioration of the internal glue lines may occur for longer fire duration time.

4.3 Fire resistance

Fire codes conventionally define failure of a specimen to correspond with loss of load-bearing capacity, loss of integrity or loss of insulation. In this study, failure of specimens under load subject to fire was defined by either of the two limit states according to Chinese Standard GB/T 9978.1-2008[18]: 1) mid-span deflection exceeding $L^2/400d$

(corresponding to L/37.5 = 64 mm for LGB-3 and LGB-4), or 2) the rate of deflection exceeding $L^2/9000d$ mm/min (2.8 mm/min) after the deflection exceeds L/30 (= 80 mm). In these failure criteria, L is the clear span, and d is the depth of the specimen. Figure 8 shows the development of mid-span deflection with fire exposure time for LGB-3 and LGB-4, having applied loads of 35 and 50% of their flexural capacity, respectively. Mid-span deflection was observed to increase with the exposure time and to increase at an increasing rate with both increased exposure time and increased applied load. The fire resistance of specimen LGB-3 and LGB-4 were 22 min and 10 min (Table 2), respectively. In both cases, failure was defined by the deflection exceeding 64 mm.

4.4 Charring rate

Bamboo has similar chemical composition as timber, consisting primarily of lignin (about 20-26% by volume), cellulose (about 40%), hemicellulose (about 30%) and about 10% vessels (voids) [19, 20]. At a microstructure level, both bamboo and timber are anisotropic, porous materials that have fibre-like structural features. Therefore, it is expected that the combustion process of bamboo is similar to that of timber. For simplification, like timber, engineered bamboo exposed to fire can be divided into three zones: the charring layer, the pyrolysis and elevated temperature affected layer, and the normal zone [13]. The charring layer forms when the temperature reaches about 300ºC, and effectively reduces the burning rate of bamboo. The temperature of the pyrolysis layer is in the range of 200~300ºC, and the elevated temperature affected layer has the temperature range of 50~200 ºC. The mass and strength of the pyrolysis and elevated temperature affected layer is smaller than normal bamboo not subject to fire or elevated temperature[15]. Finally, for the interior normal zone, the strength of the bamboo remains unaffected. The relative depths of these zones may differ somewhat for bamboo since the thermal conductivity of bamboo is typically greater than that of timber [13]. However, different than solid timber, engineered laminated bamboo, which is composed of neatly arranged slender bamboo strips joined with adhesive, may fracture along the glue lines. Bamboo scrimber, having a higher resin content may also fail through the resin, rather than the bamboo fibres.

To investigate the extent of charring, the residual geometry of the fire-exposed beams was measured from 50 mm-thick pieces cut from the beam at loading points after the charring layer was removed (see Figure 13). The residual cross-section of specimens LGBA-1 and LGBA-2 was slightly different than specimens LGB-3 and LGB-4. This may be mostly attributed to the fact that the top surface of specimens LGB-3 and LGB-4 were located slightly higher than the bottom surface of the furnace lids in order to prevent the flame getting out of the furnace. This caused the top area to not be directly exposed to fire. Specimens LGBA-1 and LGBA-2 were laid inside the furnace with the top surface covered with insulation and side surfaces were fully exposed. For laminated bamboo beams, the top and bottom surfaces were exposed to fire with the tangential direction in perpendicular to grain, while the other sides were exposed to fire with the radial direction perpendicular to grain. Knowing the original section geometry, the extent of charring was calculated. As seen in Figure 13, the bottom corners which were subjected to heat transfer from two directions, exhibited greater section loss due to charring leading to a rounding effect. Accurate measurements of the charred sections were made by exporting the images into drafting software and measuring the geometric properties of the residual sections. To simplify the calculation of the moment capacity, the residual cross-section was equated to an equivalent rectangular cross-section having the same elastic section modulus (second moment of area divided by the depth of the centroid of the cross-section) as the irregular charred beam section. The equivalent charring rate, given in Table 3, was calculated based on the equivalent rectangular section (discounting the rounding effects at the corners) and is therefore marginally greater than the average rate based on actual geometry away from corners. In Table 3, the equivalent fire duration time used to calculate the charring rate was taken as 5 minutes plus the time of the furnace fire based on the principle of equal area below the measured and ISO 834 standard fire curves considering the combustion of the beams themselves after the furnace fire was stopped. The laminated bamboo beams had a higher charring rate than the bamboo scrimber. This may be attributed to the greater density of the bamboo scrimber (Table 1). The relatively high charring rate of LGB-4 was caused by the peeling off of the lamellas from the bottom of the beam. The measured average charring rate was slightly larger than that the calculated average charring rate for specimens exposed to a heat flux of 50 kW/m^2 for 30–60 min. from cone calorimeter tests [13]. The difference was because in the cone calorimeter tests specimens were exposed to fire only on one face while those reported here are exposed on three sides, and relative short fire exposure time in this study. The charring rate of bamboo scrimber was close to the observations in the study by Xiang [21]. No apparent effect was observed of the load during the heating process on the charring rate, although the load was expected to exaggerate the charring rate of engineered bamboo due to the higher stress and possible presence of cracking and debonding.

4.5 Ultimate capacity of fire-damaged beams

The "reduced cross-section method", using an effective cross-section and normal temperature mechanical properties, is commonly used for the design of timber members exposed to fire and after exposure to fire [22]. Bamboo has similar charring performance as timber, thus, the reduced cross-section method was employed to calculate the moment capacity of the engineered bamboo beams exposed to and after exposure to fire. The failures of the tested beams were mostly triggered by tensile rupture of the bottom fibres; thus the moment capacity of the engineered bamboo beams can be calculated from the plane strain stress distribution shown in Figure 14 from equations (1) to (3).

$$\sum_{i=1}^{n} b_i \sigma_i t_i = 0 \tag{1}$$

$$M_u = \sum_{i=1}^{n} b_i \sigma_i t_i \cdot \left(y_i + y_t - \frac{d}{2} \right) \tag{2}$$

$$\sigma_i = k_t f_t \frac{y_i - (0.5d - y_t)}{y_t} \qquad \text{if} \quad y_i \geq 0.5d - y_t \tag{3-1}$$

$$\sigma_i = k_t f_t \frac{y_i - (0.5d - y_t)}{y_t} \cdot \frac{E_c}{E_t} \geq -k_c f_c \quad \text{if} \quad y_i < 0.5d - y_t \tag{3-2}$$

where, f_c and f_t are the compressive and tensile strengths of engineered bamboo from small clear specimens; k_c and k_t are reduction factors for consideration of the difference between strength from small clear specimens and full-scale structural members; b_i is the effective width of the i^{th} layer of the residual cross-section after fire exposure; and

d is the height of the original cross-section. the values of k_c and k_t were taken as 0.85 and 0.75 for laminated bamboo and 0.70 and 0.75 for bamboo scrimber [23]. Reversing the process, the fire resistance (adequate residual capacity for a specified demand) can be obtained by iteration with the fire time until the moment capacity is equal to the post-fire applied moment.

The calculated post-fire ultimate loads and fire resistance for the tested specimens are compared with test results in Table 2. In this analysis, the depth of the section was divided in to n = 10 layers. Although a greater number of layers should improve the accuracy, the calculated and experimental results are in good agreement. However, a layer-by-layer formulation (Eqs 1 – 3) is not practical for design office use. To simplify the calculation, the equations for room temperature design are employed (Eqs 4 and 5) and modified as described by Equation 6[22].

$$M_u = f_m W_n \tag{4}$$

$$W_n = \frac{b_{re} d_{re}^2}{6} \tag{5}$$

$$d_{ef} = \beta_{\mathrm{n}} t + C \tag{6}$$

where, f_m is the modulus of rupture of the beams from full-size beams; for beams exposed to three-side fire, b_{re}=b-2d_{ef}, d_{re}=d-d_{ef}; β_{n} is the reported charring rate of engineered bamboo and conservatively suggested to be taken as 0.9 mm/min and 0.7 mm/min for the laminated bamboo and bamboo scrimber materials considered in this paper, respectively; and C is a constant considering the influence of pyrolysis and elevated temperature affected zone and suggested to be taken as 7 mm and 5 mm for the laminated bamboo and bamboo scrimber considered in this paper, respectively. In

EC5 [22], C was suggested to be 7 mm for timber. The values in this study were selected considering that the density of laminated bamboo lies in the range of timber species commonly used in Europe while the bamboo scrimber is more dense than timber specimens commonly used in Europe. Further studies are required to improve these values as the test data in this paper is limited.

The calculated ultimate capacity after fire and fire resistance of the engineered bamboo beams tested in this study determined from the simplified method are also compared with test results in Table 2. The proposed simplified method can predict the ultimate capacities after fire and fire resistance of the engineered bamboo beams tested with acceptable accuracy.

5. Conclusions

This paper has presented the results of an experimental study to investigate the fire resistance and post-fire performance of engineered bamboo beams. In total, nine tests were carried out including two tests in which the beams were loaded while exposed to a standard fire and seven flexural tests of beams following exposure to a standard fire. Charring depth was measured after the tests. Both sectional analysis and proposed simplified methods based on the reduced cross-section method were developed to calculate the residual moment capacity of beams in and after fire exposure. The following conclusions are drawn:

(1) All test specimens exhibited flexural failure triggered by tensile fracture of the extreme tension fibres.

(2) The control specimens – having no fire exposure – exhibited higher initial

stiffness and ultimate loads than the fire exposed beams. Stiffness and ultimate loads of the engineered bamboo beams decreased with increased fire exposure time.

(3) The strain distribution at the mid-span cross-section was essentially linear for all specimens; this indicates no premature breakdown of the adhesive system used and permits simple sections analysis to be carried out. However, for longer fire duration time than considered in this study, further research is required, since higher temperatures may develop at greater depths.

(4) Fire resistance of laminated bamboo beams decreased with increased constant applied load.

(5) As the bottom corners of the beams are subjected to heat transfer from two directions when beams were exposed to a three-sided fire, greater charring is observed at these corners leading to rounding of the cross section. Laminated bamboo had a higher charring rate than bamboo scrimber, due to the lower density of the laminated bamboo.

(6) A proposed simplified calculation can be used to predict the fire resistance and ultimate capacity of engineered bamboo beams following short durations of exposure to standard fire. More results are required to further improve or validate this calculation for other fire exposures and durations.

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Table 1 Material properties of engineered bamboo used in this study.

	test method	laminated bamboo	bamboo scrimber
density	ISO 3131	663 kg/m^3	984 kg/m^3
moisture content	ISO 3130	15.2%	9.2%
modulus of elasticity (small clear specimen)	ISO 3349	12020 MPa	15730 MPa
tensile strength parallel to grain	ISO 3345	122.0 MPa	126.4 MPa
compressive strength parallel to grain	ISO 3787	47.8 MPa	61.8 MPa
modulus of rupture (small clear specimen)	ISO 3133	140.4 MPa	138.3 MPa

Table 2 Summary of bamboo specimen geometry and test results

	Specimen	Geometry (mm)	Furnace fire duration (min)	Ultimate load (kN)			Fire resistance (min)			
				observed	Eq. 2	Eq. 4	Load (kN)	observed	Eq. 2	Eq. 4
Laminated	LGB	225×100×2630	0	190.0	186.7	-	-	-	-	-
	LGBA-1	225×100×2630	10	100.3	99.6	92.6	-	-	-	-
	LGBA-2	225×100×2630	25	43.3	44.2	43.8	-	-	-	-
	LGB-3	225×100×2630	-	-	-	-	66.5	22	22.8	15.0
	LGB-4	225×100×2630	-	-	-	-	95.0	10	11.1	12.6
Scrimber	SGB	140×100×2430	0	68.1	70.5	-	-	-	-	-
	SGBA-1	140×100×2430	10	45.5	47.1	37.1	-	-	-	-
	SGBA-2	140×100×2430	25	16.4	17.2	21.7	-	-	-	-
	SGBA-3	140×70×2430	10	22.5	23.0	21.0	-	-	-	-

Table 3 Charring rate of engineered bamboo beams

Specimen	Equivalent fire duration (min)	Initial geometry (mm)		Charred geometry (mm)		Charring rate (mm/min)		Average charring rate (actual geometry) (mm/min)	Equivalent charring rate (equivalent rectangular geometry) (mm/min)
		b	d	b	d	β_b	β_d		
LGBA-1	15	100	225	84	213	0.53	0.80	0.67	0.89
LGBA-2	30	100	225	56	194	0.73	1.03	0.88	0.98
LGB-3	27	98	223	63	199	0.65	0.89	0.77	0.82
LGB-4	15	98	222	83	212	0.50	0.67	0.58	0.95
SGBA-1	15	100	140	94	128	0.20	0.80	0.50	0.61
SGBA-2	30	100	140	70	117	0.50	0.77	0.63	0.83
SGBA-3	15	70	140	54	130	0.53	0.67	0.60	0.67

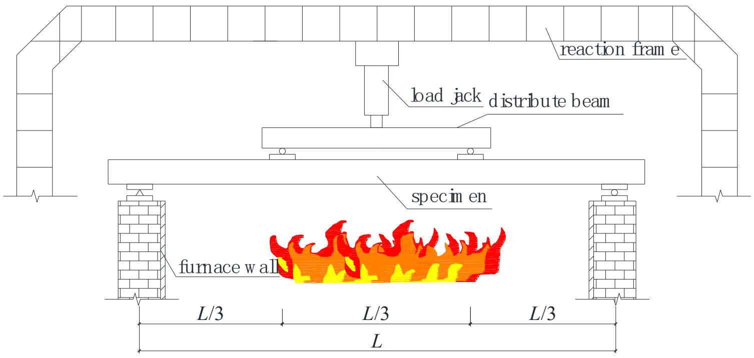
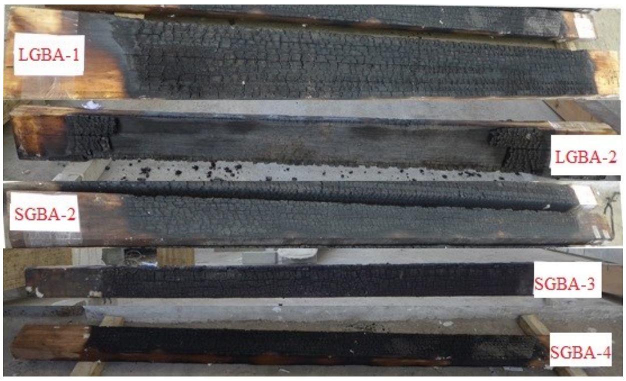


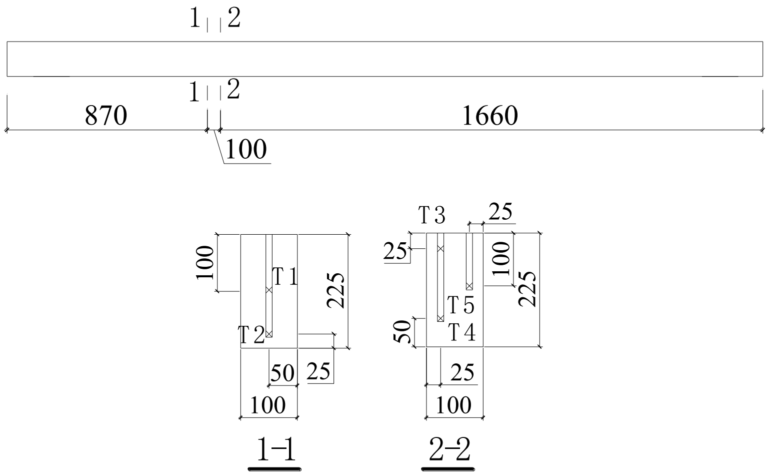
Figure 1 Test setup for fire resistance tests. Post-fire and control tests are conducted using same dimensions.

a) specimens in furnace before fire exposure

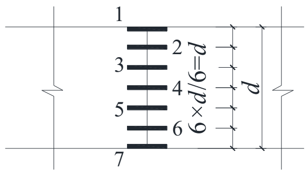


b) specimens following fire conditioning

Figure 2 Test specimens.

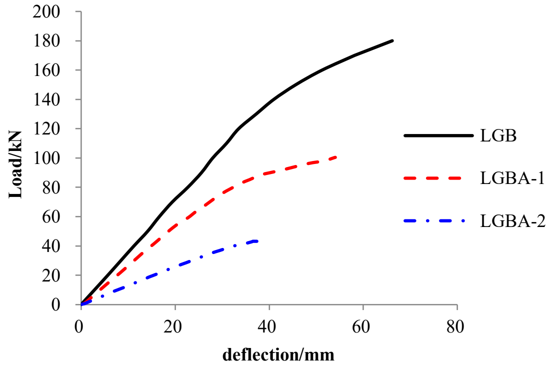


(a) thermocouples in LGB-3 and LGB-4

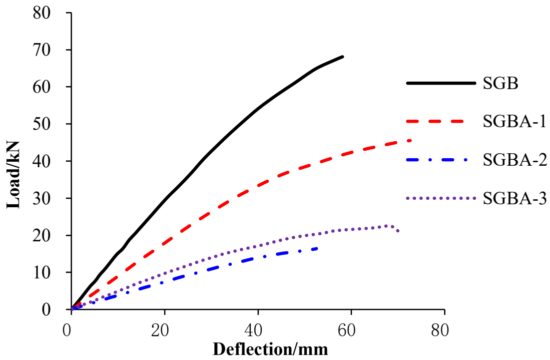


(b) strain gauges on all beams subject to flexure in ambient environment

Figure 3 Arrangement of thermocouples and strain gauges (Unit: mm)



(a) Laminated bamboo



(b) Bamboo scrimber

Figure 4 Load-deflection curves for specimens tested after fire exposure.

(a) LGB

(b) LGBA-1

(c) LGBA-2

Figure 5 Failure modes of laminated bamboo specimens.

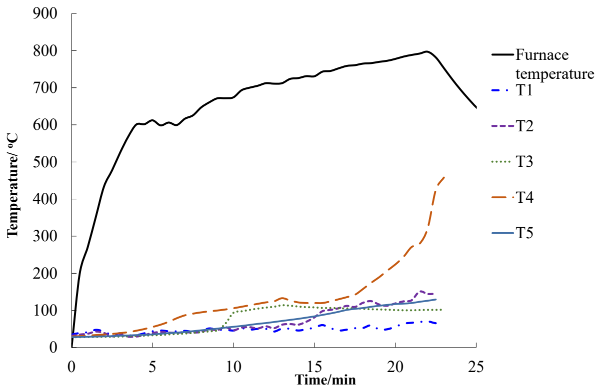
(a) SGB

(b) SGBA-1

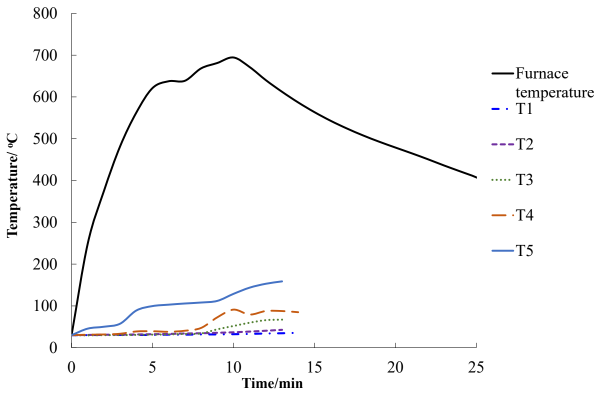
(c) SGBA-2

(d) SGBA-3

Figure 6 Failure modes of bamboo scrimber specimens.



(a) LGB-3



(b) LGB-4

Figure 7 Temperature-time curves of typical specimens.

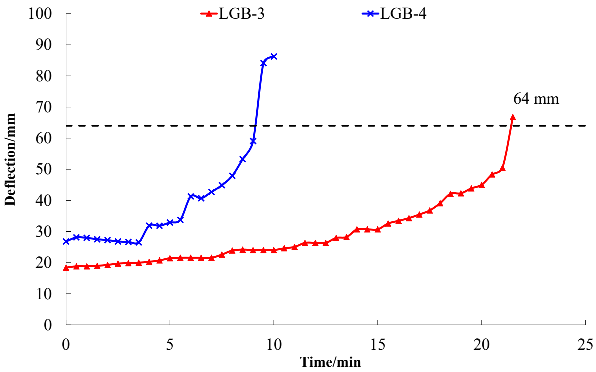
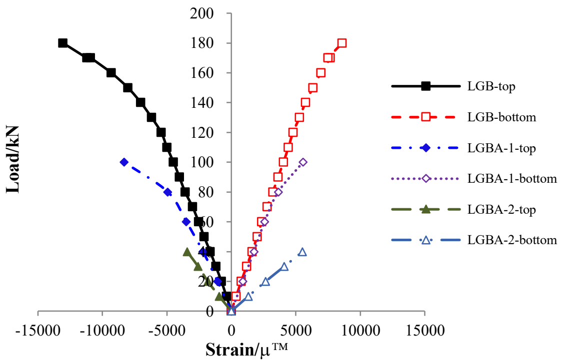


Figure 8 Development of mid-span deflection of specimens tested for fire resistance.

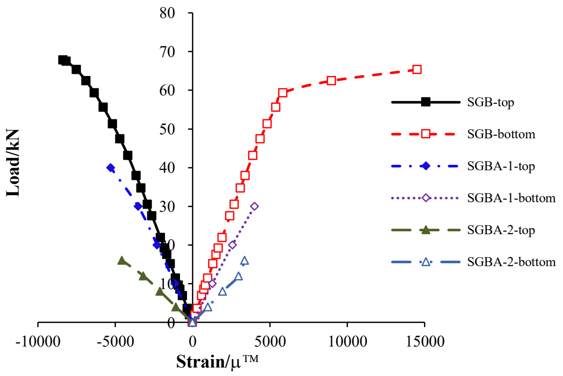
a) during fire tests

b) after fire tests (top:LGB-3; bottom: LGB-4)

Figure 9 Fire resistance tests

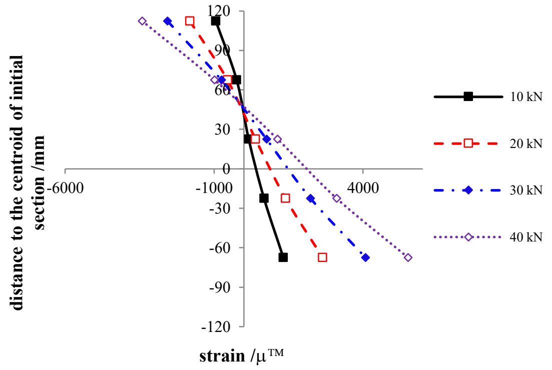


(a) Laminated bamboo

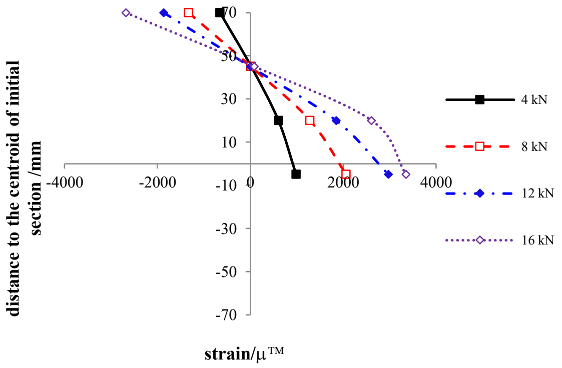


(b) Bamboo scrimber

Figure 10 Load-strain curves of tested beams.



(a) LGBA-2



(b) SGBA-2

Figure 11 Strain distribution of mid-span cross-section for typical specimens.

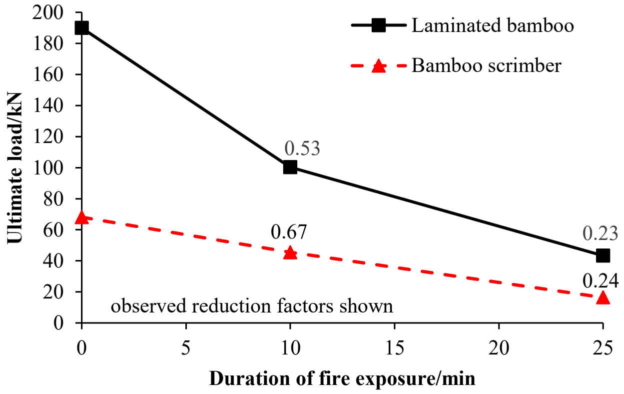
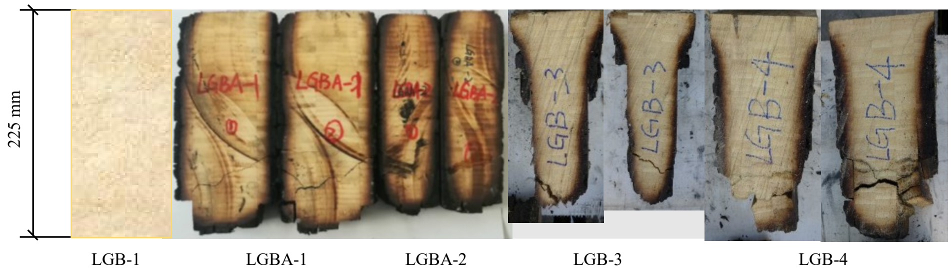


Figure 12 Comparison of ultimate loads of beams having different fire exposure duration



(a) laminated bamboo

(b) bamboo scrimber

Figure 13 Residual cross-sections of specimens.

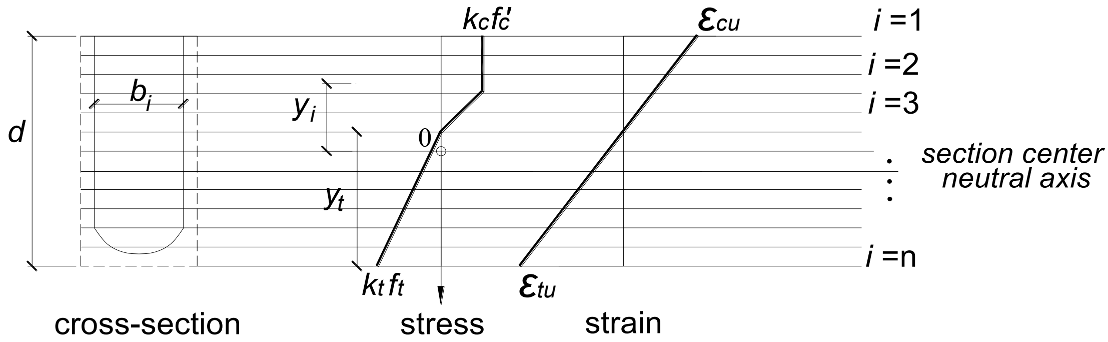


Figure 14 Stress and strain distribution at ultimate state in beams.