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Influence of temperature on the compressive properties of engineered bamboo boards used for GluBam structures

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ABSTRACT

The understanding of engineered bamboo structures' fire performance is vital for the application of such biomaterials, to meet the safety requirements of structures during a fire. The theoretical model of fired engineered bamboo structures based on the 1) reasonable models of fire, 2) bamboo combustion behavior, 3) heat affected zone model, and 4) the influence of temperature on the engineered bamboo mechanical properties. Thus, this research aims to determine the influence of increasing temperature, from 20℃ to 220℃, on the mechanical properties of commercial 30 mm engineered bamboo boards used for glubam structures shortly after a heating period, from one to two hours. The research results reported in this research is the base for safety assessment and degradation of mechanical properties of modern bamboo structures under elevated temperature and fire.

1. INTRODUCTION

The engineered bamboo (EB) boards can be used as a sustainable construction material with high-performance by terms of high strength-to-density ratio, excellent thermal insulation performance, and easy-to-manufacture. In recent years, this material has been successfully used for residential buildings, bridges, and wind blades. The researches on mechanical performance of GluBam structures and structural elements based on such boards has been conducted by Xiao et al. since 2009 (Xiao 2013, Xiao 2010, Xiao 2012, Xiao 2014a, Xiao 2014b, Wang 2017, Wu 2018, Li 2019).Two types of engineered bamboo boards are normally used for GluBam structures, namely thick-strip unidirectional laminated bamboo and thin-strip multidirectional laminated bamboo, as shown in Fig. 1. It is manufactured through a two-step lamination process. The first process is to integrate bamboo strips cut from bamboo culms into bamboo boards of 20 to 40 mm thick by lamination under pressure and elevated temperature (about 5 MPa and 150℃). The second process is pressure lamination of the elements cut from the boards under room temperature, similar to the process of manufacturing glulam. The

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glubam and the engineered bamboo boards can be categorized into the thick-strip lamina and thin-strip lamina. In the first step process, the thick-strip laminated glubam is made by pressure gluing a few layers of relatively thicker bamboo strips (5~8 mm thick and about 20~25 mm wide). On the other hand, the thin layer laminated glubam is typically made by laminating netted mats of approximately 2 mm thick 20 mm wide bamboo strips. The bamboo boards are typically manufactured as plates with a size of about 2000~2500 mm long and 80~1200 mm wide. The thick-strip glubam boards generally are made unidirectional with all the strips aligned in the longitudinal direction, but can also be made bidirectional as cross-laminated bamboo or CLB. For the thin-strip glubam boards, they are generally bidirectional with typical ratios of longitudinal to transverse bamboo strips of 4:1 ~ 7:1 for making columns or girders, and 1:1 for making wall panels. The engineered bamboo boards can be stacked for transportation of mass quantities.

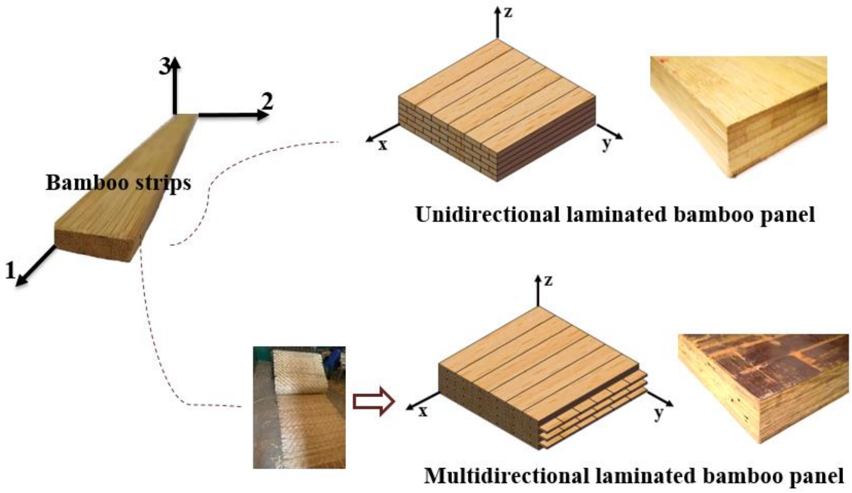


Fig. 1 Engineered bamboo boards for GluBam

An accurate method to estimate the mechanical properties of engineered bamboo products under high temperatures is the prerequisite for the safety and vast application of this environmentally friendly material in the engineering field. In this research, the compressive properties of EB boards were studied with increasing environmental temperature from 20℃ to 220℃, shortly after the heating process, in 15 minutes. Meanwhile, the compressive specimens under 130℃ environmental temperature were tested in three different conditions, by terms in the high environment temperature condition, shortly after heating condition and conditioned in a humidity chamber with humidity of 65% RH and temperature of 20℃ for more than 48 hours. Prominent different compressive properties were noticed for the same specimens with different conditions. The influence of changing strength and stiffness values of EB materials during and after a fire event should be taken into consideration for the fire safety assessment of bamboo structures.

2. MATERIALS AND METHODS

2.1 Materials

Two types of engineered bamboo products were tested in this research, namely unidirectional laminated bamboo and multidirectional laminated bamboo, as shown in Fig. 1. The mechanical properties of these boards were studied by recent research (Li 2020). Table 1 gives the main mechanical proprieties of 30 mm engineered bamboo boards studied in this research.

Table 1 mechanical proprieties of 30 mm bamboo boards

Property		Type of board	Strength	Modulus
			Value (MPa)	
Tension	$f_{t,x}$	U	119.3 (22.0)	10508 (1025)
		M	80.5 (17.3)	10746 (761)
	$f_{t,y}$	U	5.9 (1.1)	NA
		M	13.3 (2.1)	NA
Compression	$f_{c,x}$	U	57.7 (4.7)	9777 (769)
		M	39.5 (7.0)	9810 (794)
	$f_{c,y}$	U	14.7 (1.1)	NA
		M	29.1 (3.4)	
	$f_{c,z}$	U	12.3 (1.2)	
		M	30.2 (5.2)	
Bending	$f_{m,xz}$	U	104.6 (7.5)	8682 (764)
		M	94.5 (10.9)	9585 (684)
	$f_{m,xy}$	U	104.9 (7.6)	9052 (599)
		M	101.1 (9.7)	11390 (740)
	$f_{m,yz}$	U	10.2 (2.8)	NA
		M	39.3 (7.3)	6025 (505)
	$f_{m,yx}$	U	9.3 (1.5)	NA
		M	26.7 (2.6)	3805 (458)

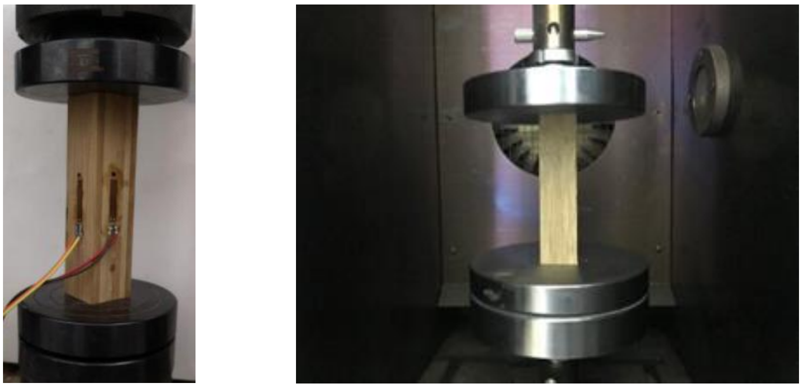
Note: 1. Stand deviation of corresponding elastic values are given in the bracket; 2. For $f_{m,ij}$, the subscript *i* indicates that the stress is acting on a plane normal to the *i*-axis, *j* is the loading direction. 3. For y and z loading directions of both unidirectional and multidirectional bamboo boards, the compression strength is the stress at the proportional limit.

2.2 test methods

Two types of specimens were used in this research, and the sizes are 30 mm×30 mm × 30 mm and 30 mm×30 mm×120 mm, respectively. Eight temperature ranges of 20℃, 40℃, 70℃, 100℃, 130℃, 160℃, 190℃, and 220 ℃ are used in this research. Among which 20℃ is the control group and the duration of each group in other test groups are 1 hour, 1.5 hours, and 2 hours. Five repetitions are used for each group of test specimens. All specimens conditioned in a humidity chamber with humidity of 65% RH and temperature of 20℃ for more than 48 hours before the test. The tests were conducted shortly after the three different designed heating hours, which is less than 15 minutes in this research. An aspherical loading head was used to ensure axial compression. The loading rate was 2.0 mm/min. The compression stress is calculated using Eq.1, with an accuracy of 0.1 MPa.

$$\sigma_x = \frac{P_{\max}}{bt} \qquad (1)$$

where σ_x is the compressive strength of bamboo in the x-direction, in MPa; P_{max} is the failure load, in N; b is the width of the test piece, in mm; t is the thickness of test piece, in mm.



(a) after heating (b) during heating
Fig. 2 Compressive test of EB boards

Meanwhile, in order to have a comprehensive understanding of the high-temperature performance of EB materials during and after a fire event, the unidirectional laminated 120 mm height compressive specimens under 130℃ were tested under two more different conditions as shown in Fig. 2, during 130 ℃ temperature and conditioned in a humidity chamber with humidity of 65% RH and temperature of 20℃ for more than 48 hours.

3. RESULTS AND DISCUSSION

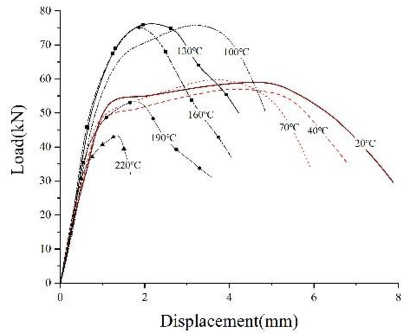
3.1 Failure modes

The failure modes of two types of EB boards with 1.5 hours heating period are illustrated in Fig. 3. Similar failure modes are noticed for specimens with different heating periods. It is interesting to note that different failure modes are noticed for specimens with different heating temperatures. Out-of-plane bulking failures are noticed for specimens under reference temperature and 70℃ heating history. Kink bands shear failures are noticed for the specimens with 100℃ heating temperatures. For specimens with heating temperature from 130℃ to 220℃, delamination is the typical failure modes of EB boards noticed in this research.

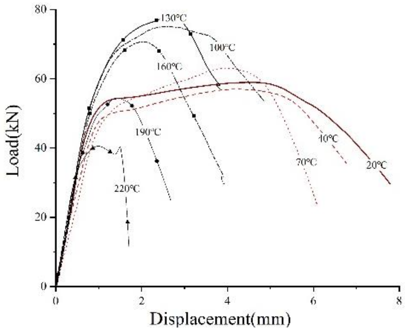
3.2 load-displacement curves

The load-displacement curves of two types of EB boards shortly after heating (in 15 minutes in this study) with different specimens' height are given in Fig. 4(a)-(f). The elastic response of EB under compressive forces less than $0.4F_u$ is relatively

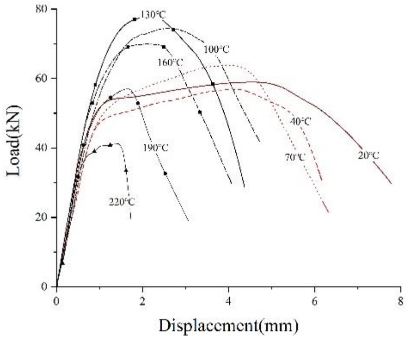
Fig. 3 The failure mode of EB boards (1.5 hrs. heating)



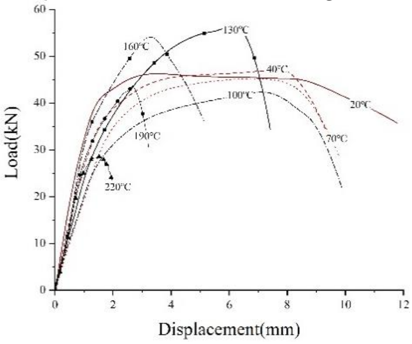
(a) U Specimens in 30mm height, 1 hr



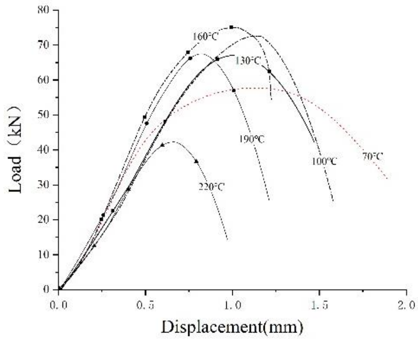
(b) U Specimens in 30mm height, 1.5 hrs



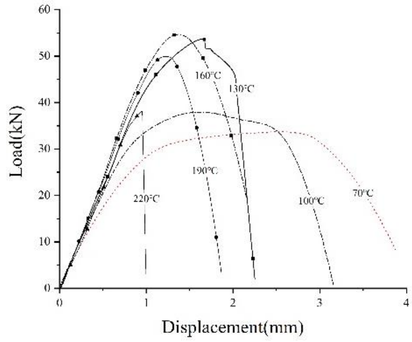
(c) U Specimens in 30 mm height, 2 hrs



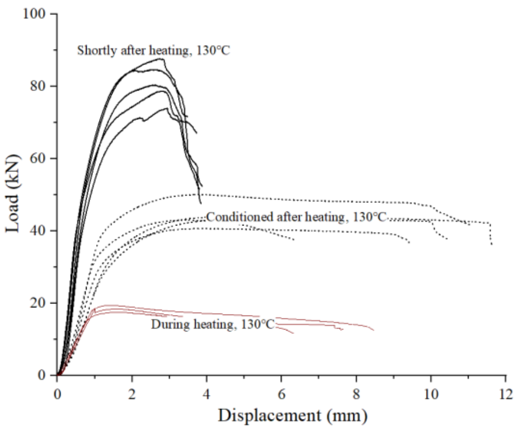
(d) U Specimens in 120 mm height, 1.5 hrs



(e) M Specimens in 30 mm height, 1.5 hrs



(f) M Specimens in 120 mm height, 1.5 hrs



(g) U Specimens in 120 mm height, 1.5 hrs

Fig. 4 Load-displacement curves of EB boards under compression at high temperature independent of increasing environmental temperatures from 20℃ to 220℃. The load-displacement curves are almost the same for specimens with environmental temperature from 20℃ to 70℃. Thus, it is reasonable to conclude that the compressive performances of bamboo structural elements are stable for normal service temperature conditions. The ultimate compressive capacity of EB increase obviously when the environmental temperatures are 100℃, 130℃, and 160℃. For compressive specimens with heating environment temperatures higher than 100℃, The plastic plateau noticed for specimens under 100℃ is disappear along with the brittle failure modes are noticed, as shown in Fig. 3. The compressive strength for unidirectional laminated engineered bamboo boards is decreased to 0.7 times of the reference strength values when the heating environmental temperature is 220℃. For multidirectional laminated bamboo boards, increasing strength values are noticed for 120 mm height specimens, whereas it is decreased to 0.8 times of the reference strength values, under 220℃ heating temperature for 1.5 hours. More researches are required to understand the mechanism behind it.

The load-displacement curves of unidirectional laminated bamboo boards, under three different heating conditions with the same heating temperature, are given in Fig. 4(g). Three groups of specimens, cataloged as during the heating, shortly after the 1.5 hours heating and conditioned 48 hours after the heating, are tested. It is interesting to notice that the compressive behaviors are changed dramatically after the heating event. It is revealed that the mechanical properties of bamboo are changed during a fire event, and more researches are required for a deep understanding of this phenomenon, which is necessary for the safety management strategy design of bamboo structures under fire event.

3.3 parametric analysis

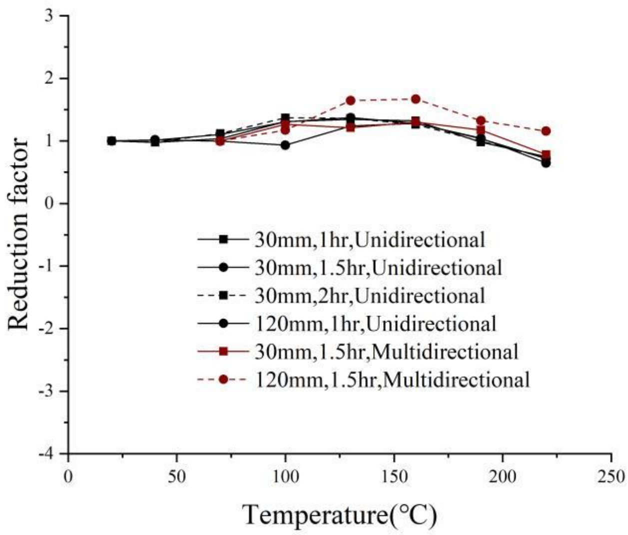


Fig. 5 Strength reduction factor of bamboo with different heating conditions

As shown in Fig. 5, based on the original test data, the influence of various parameters on the high-temperature performances of bamboo materials are studied in this research. Two types of engineered bamboo boards show similar high-temperature performance with increasing heating temperature. For 120 mm height specimens under 190℃ heating for 1.5 hours, the multidirectional laminated bamboo specimens show an increasing bearing capacity, whereas the unidirectional laminated bamboo specimens show a decreasing bearing capacity. In other words, the multidirectional laminated bamboo shows a higher high-temperature resistance capacity in this research. Three different heating periods are used in this research; however, small differences in the compressive behaviors are noticed for the specimens with different heating hours, as shown in Fig. 5. Thus, the 1.5 hours heating period is suggested for future researches, which is more than the fire resistance time (1 hour) required for timber structures in China (GB 50016 2014).

The 30 mm height is suggested by the ISO (ISO 13061 2017) and Chinese stand (GB/T 1935 2009) for wood materials with the consideration of so-called clear wood specimens to exclude the influence of wood knots. The 120 mm height is given by ASTM standard (ASTM D143 2014), and it is adopted by the previous studies on the mechanical properties of engineered bamboo products (Li 2020). As shown in Fig. 3, the changes in failure modes can be distinguished easily with relatively taller sample height. The height of specimens has little influence on the high-temperature resistance performances of unidirectional bamboo boards. For multidirectional laminated boards, it seems that the 120 mm height specimens have a slightly better high-temperature resistance ability than 30 mm height ones. Many pieces of research indicate the prefabricated patterns have an apparent influence on the thermal performance of composite materials (Gibson 2016). However, a similar mechanism for biocomposite materials, such as bamboo, is still not clear up to now.

4. CONCLUSION

The compressive performances of two types of engineered bamboo panes shortly after a heating environment were experimentally studied in this research. Strength degradation is noticed for specimens with a heating temperature of more than 100℃. The compressive test of specimens under three different conditions, cataloged as during the heating, shortly after the heating and conditioned 48 hours after the heating, indicating that the mechanical properties of bamboo material would change obviously after a fire event. More researches are required for a reasonable understanding of this phenomenon. Parametric analysis of various parameters, including the type of bamboo boards, heating time, and size of specimens, are analyzed in this research.

The test results reported in this research can be used as a reference for the fire resistance performance of engineered bamboo structures. Meanwhile, the specimen size of $t \times t \times 120$ mm, with t is the thickness of bamboo boards, and 1.5 hours heating period is recommended for future studies on the high-temperature performance of engineered bamboo products.

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