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Mechanical behaviour of bamboo at elevated temperatures – Experimental studies

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Abstract:

The growing demand for sustainable load-bearing materials drives the need for understanding the various design considerations these pose within the modern built environment. Engineered bamboo is a material with outstanding physical and mechanical properties, in addition to producing a minimum carbon footprint. However, extensive research is needed before engineered bamboo can be used with the confidence conferred to other more conventional building construction materials. When aiming for higher and larger bamboo-based structures, load-bearing behaviour during and after fire becomes a key consideration. This paper describes the outcomes of a comprehensive study conducted to understand the mechanical behaviour of bamboo (*Phyllostachys pubescens* species) at elevated temperatures; more specifically investigating the reduction of compressive and tensile strength, as well as the Modulus of Elasticity (*MoE*) up to 250°C. Findings from this work show that at 200°C, bamboo retains 20%, 42% and 70% of the compressive strength, tensile strength and modulus of elasticity at ambient, respectively. The results presented herein, which provide thorough understanding of strength and elasticity reduction at elevated temperatures, enable the development of stress-strain constitutive models that will constitute the basis for designing fire-safe bamboo structures.

Keywords: bamboo structures; structural fire design; compressive strength; tensile strength; elastic modulus.

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1 Introduction and background

In recent years bamboo has gained popularity in the built environment, mainly due to its low cost, high mechanical strength, appealing aesthetics, flexibility, and very low, or even positive, environmental impact [1]. Bamboo has one of the highest renewable rates when compared with other natural construction materials [2]. The low energy consumption required for its extraction and processing, in addition to its ability to sequester high amounts of CO_2, makes bamboo an attractive alternative for the industry [2, 3].

Bamboo is a grass (not a tree), which only experiences vertical growth with no radial growth. The culm is hollow, tapered and segmented. The parts of the culm are usually labelled as nodes and internodes. The nodes are a diaphragm composed of fibres that change direction. The internodes are fundamentally hollow tubes, with axially oriented cells. Typically, the walls of a bamboo culm are composed of parenchyma cells (50%), fibre bundles (40%), and conducting tissues (10%) [4].

In the past two decades, laminated bamboo and other engineered bamboo products have been developed to overcome some of the barriers experienced in round bamboo construction. Building with laminated bamboo can offer more efficient and simple connections, larger and standardised cross-sections, lower dispersion in mechanical properties, and higher value for producers [5, 6]. Mechanical performance of bamboo has been studied extensively. Its mechanical properties are superior to many species of softwood, and in general, they can be paired with some hardwoods [7, 8].

Traditionally, bamboo has been used as a primary load-bearing material for low-rise constructions in rural or remote areas where it can be easily found and exploited [9, 10]. However, there is a real need for building in highly populated urban areas where fire safety is a governing design consideration. In that sense, bamboo has risen concerns due to its combustible nature and its mechanical performance when subjected to elevated temperatures [11]. With the potential for bamboo to be used in urban environments and mid-rise structures, the need for demonstrating adequate performance during and after a fire event is essential [13]. Principally, if structural integrity must be achieved to develop a sound fire safety strategy, which is critical for mid- and high-rise buildings [12-14]. A comprehensive description of stress-strain curves at elevated temperatures, as well as the failure mechanisms, will allow the development of analytical and computational models to predict the structural behaviour of load-bearing bamboo members during a fire. Although other key issues have been identified to deliver a sound fire safety strategy like understanding the conditions to sustain combustion after the burnout [15] or the characteristics for the occurrence of char call-off [16, 17], this study has been mainly focused on the mechanical response of bamboo at elevated temperatures.

Understanding the reduction in the mechanical properties at elevated temperatures is essential to predict the behaviour of load-bearing elements and structures during and after fire [18]. Similar to other natural grown materials like timber, bamboo experiences a thermo-chemical degradation/pyrolysis at temperatures above 150°C [19, 20]. Between ambient and 150°C, dehydration and phase changes are known to influence the mechanical response of bamboo [21], and a reduction on the strength, elasticity, and ductility has been observed. Bamboo loses its capacity to transfer load at temperatures above 250°C. Prior researchers have studied the reduction in the mechanical properties of some bamboo products at elevated temperatures [18, 22, 23]; however, few studies have reported the reduction in the mechanical strength and elasticity of round and laminated bamboo at elevated temperatures [24, 25].

The aim of this work is to investigate the reduction in the compressive strength, tensile strength, and Modulus of Elasticity (*MoE*) for bamboo at elevated temperatures. Stress-strain curves, and failure modes are studied as well. Outcomes of this study will establish the basis to conduct structural fire engineering analysis and design of load-bearing bamboo structures.

2 Materials and sample preparation

Compressive strength test specimens were fabricated using a 3 to 5-year-old Chinese *Phyllostachys pubescens*, with a measured density between 580-651 kg/m^3 and moisture content between 4.6-7.6% (by mass). Laminated bamboo was manufactured using Phenol Resorcinol Formaldehyde (PRF) glue. Sample dimensions, 40mm x 70mm x 240 mm, were chosen based on recommendations shown in the European standard EN 408 for testing the mechanical properties of laminated timber products [26]. Compressive strength test specimens had a width-to-height ratio of 1:6.

Direct tensile strength test specimens were fabricated using the same bamboo species as that use for compressive strength specimens, at the same age. In this case, bamboo strips (not laminated) with a measured density between 841-914 kg/m^3 and a moisture content of 9.1% (by mass) were prepared. Sample dimensions were chosen based on recommendations shown in ASTM D143-94 [27] and ISO 22157 [28].

3 Experimental methodologies

The adopted procedures to heat up and test the mechanical behaviour of test specimens to obtain the compressive and tensile strength at high temperatures are presented in this section. A novel experimental test setup was used to heat test specimens (in compression or in tension) to a target temperature. MoE of bamboo at elevated temperatures was indirectly measured using the crosshead displacement calibrated prior to testing using control samples with strain-gauges; this is thoroughly explained herein.

3.1 Heating conditions

3.1.1 Samples tested in compression

A preliminary thermal characterisation study was completed to guarantee steady-state conditions in the sample before applying the compressive load. Specimens were placed inside an MTS environmental chamber where surface and in-depth temperatures were measured with K-type thermocouples to understand the thermal gradients and inner temperatures within the solid of bamboo specimens when they were being heated. Specimens where heated for target temperatures between ambient and 250°C, at a heating rate of 5°C /min. The steady-state temperature of the sample was assumed to be reached when the rate of temperature at the centre of the specimen was less than 0.4 °C/min.

Figure 1(a) presents the surface and internal temperature measured in the centre of three compressive specimens placed within the environmental chamber as well as the change of internal temperature, which allowed to determine the time required to reach the steady-state condition. Correlations between the surface temperature and internal temperature in the specimen at steady state were derived to predict the temperatures in the centre of the specimen without affecting its integrity during the mechanical experiment, as it is presented in Figure 1(b).

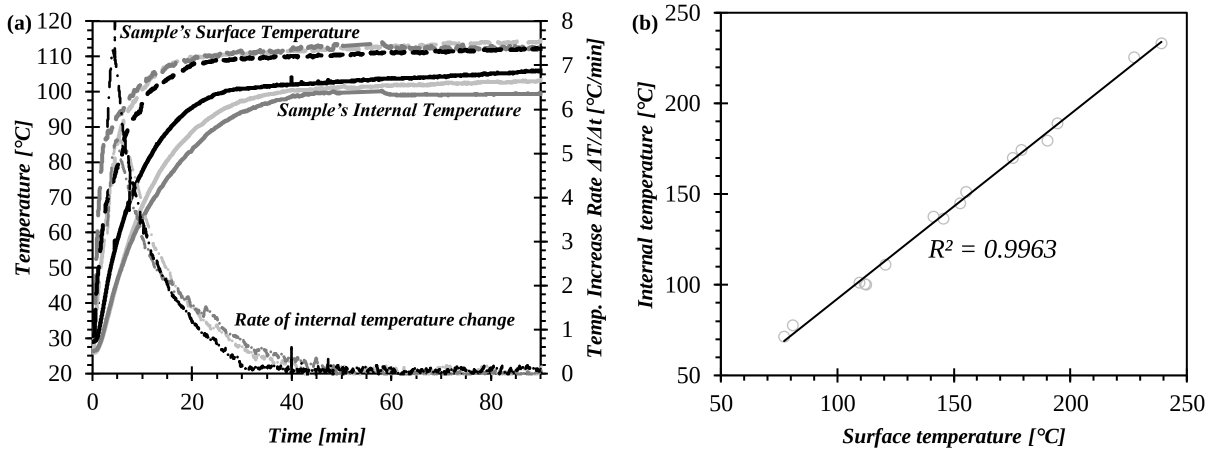

Figure 1. (a) Temperature on the surface and in the centre of compressive specimens at 120°C. The rate of internal temperature change against time to exposure is presented in the secondary axis. (b) Temperature on the surface and in the centre of specimens at the steady-state condition.

3.1.2 Samples tested in tension

Specimens tested in tension had a thinner cross-section than specimens for the compressive tests, and the time required to achieve a steady-state temperature in the cross-section was calculated using the characteristic time equation. Tensile samples were heated at a rate of 25°C /min with a heating blanket for different times according to the desired temperature, and the surface temperature was controlled with a thermocouple connected to a PID controller that enables to keep the temperature constant at the surface. The mechanical test was conducted once the specimen had achieved the steady-state condition, and the internal temperature in the specimen was reported as the surface temperature measured in the specimen at the moment of the test. The set-ups for heating the samples in compression and tension can be seen in Figure 2.

3.2 Loading test setup

3.2.1 Compressive strength tests

Compressive strength tests were conducted following the procedures established in EN 408 [26]. Once the sample had achieved a steady-state temperature along the whole cross-section, the compressive strength test was performed loading the sample with a constant deformation rate of 0.6 mm/min. All specimens were loaded at elevated temperatures with the use of a 1MN MTS hydraulic testing machine assembled with an MTS environmental chamber series 651. Once the failure was achieved, the specimen was unloaded and removed from the chamber.

3.2.2 Tensile strength tests

The tensile strength tests were conducted following the procedures established in the ASTM D143-94 [27]. Once the specimen had achieved a constant temperature along the whole cross-section, the tensile strength test was conducted loading the specimen with a constant deformation rate of 0.6 mm/min. Specimens were loaded in an Instron Machine with a 5kN load cell capacity. All the specimens presented a tensile failure in the heated zone, and the heating blanket was removed immediately after the failure. Figure 2 (a) and (b) shows the experimental set-up and the dimensions of specimens for the compressive and tensile strength tests, respectively.

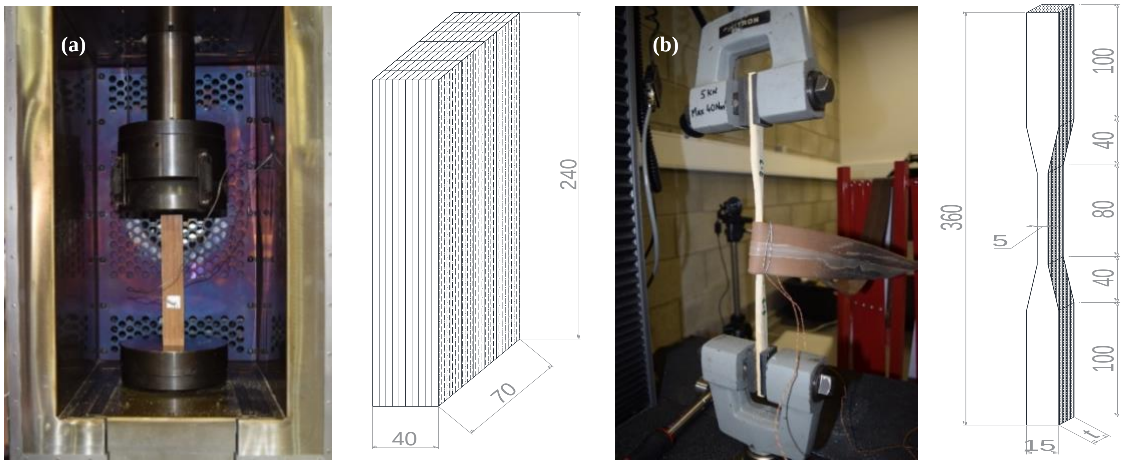

Figure 2. (a) Test setup and specimen dimensions for performing compressive strength tests (b) and tensile strength tests on bamboo at elevated temperatures.

3.2.3 Modulus of elasticity tests

A novel methodology was developed to measure the reduction in *MoE*. Specimens were loaded with three different loading cycles ambient temperature and at elevated temperature. Strain gauges (10 mm long, 120 Ω resistance and a 2.16-gauge factor) were used to obtain a correlation between the machine crosshead displacement, and the deformation of the specimen at different load levels. These correlations were used later to obtain the deformation of the sample for the various loading cycles at ambient and elevated temperatures (for compression and tension tests).

The reduction in *MoE* was calculated based on the difference between *MoE* obtained at ambient and at elevated temperatures for each targeted temperature, as it can be seen from Figure 3, where *MoE* was obtained for the same sample tested at ambient temperature and at 120°C. The *MoE* was obtained following the procedures described in the ISO 22157 [28], as the slope of the stress-strain curve in the elastic range, when the stress is between 10% and 40% of the maximum stress obtained during the test. The same procedure was followed to achieve the reduction in *MoE* at other targeted temperatures tested in compression as well as in tension.

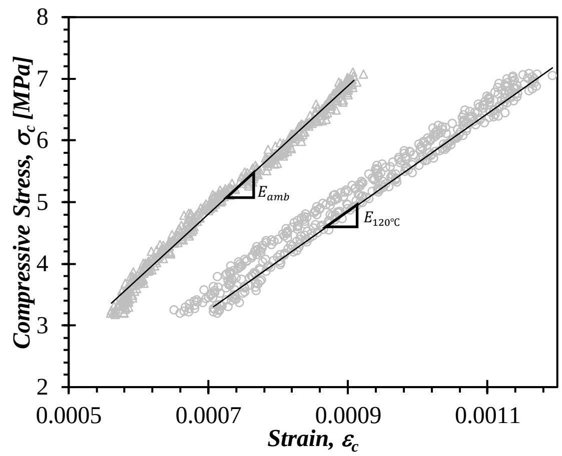

Figure 3. Stress-strain elastic curves to obtain the *MoE* at ambient and elevated temperatures.

4 Results

4.1 Compression

4.1.1 Stress-strain curves and failure mechanisms

Compression stress-strain curves for samples tested at ambient conditions and at elevated temperatures are shown in Figure 4. In general, bamboo specimens tested in compression show three different behaviours for temperatures between ambient and 150°C: (1) a well-defined linear elastic range, (2) an elastic-plastic range, and (3) an inelastic range where there is a continuous reduction of strength with large plastic deformation. There are mainly two regions in the stress-strain curves of specimens tested at temperatures above 150°C: (1) a linearly elastic range until the maximum stress is reached and (2) an inelastic range where there is a continuous reduction of strength with large plastic deformation.

Based on the outcomes of the stress-strain curves, there is a reduction of the maximum compressive strength as a function of temperature, an increase of the deformation at the failure between ambient and 150°C, and a reduction of the deformation at the failure for temperatures above 150°C. Bamboo has an elastic-plastic behaviour and its ductility increases for temperatures between 100 and 150°C; however, above 150°C, a different failure mechanism, as well as a different shape in the stress-strain curve is observed.

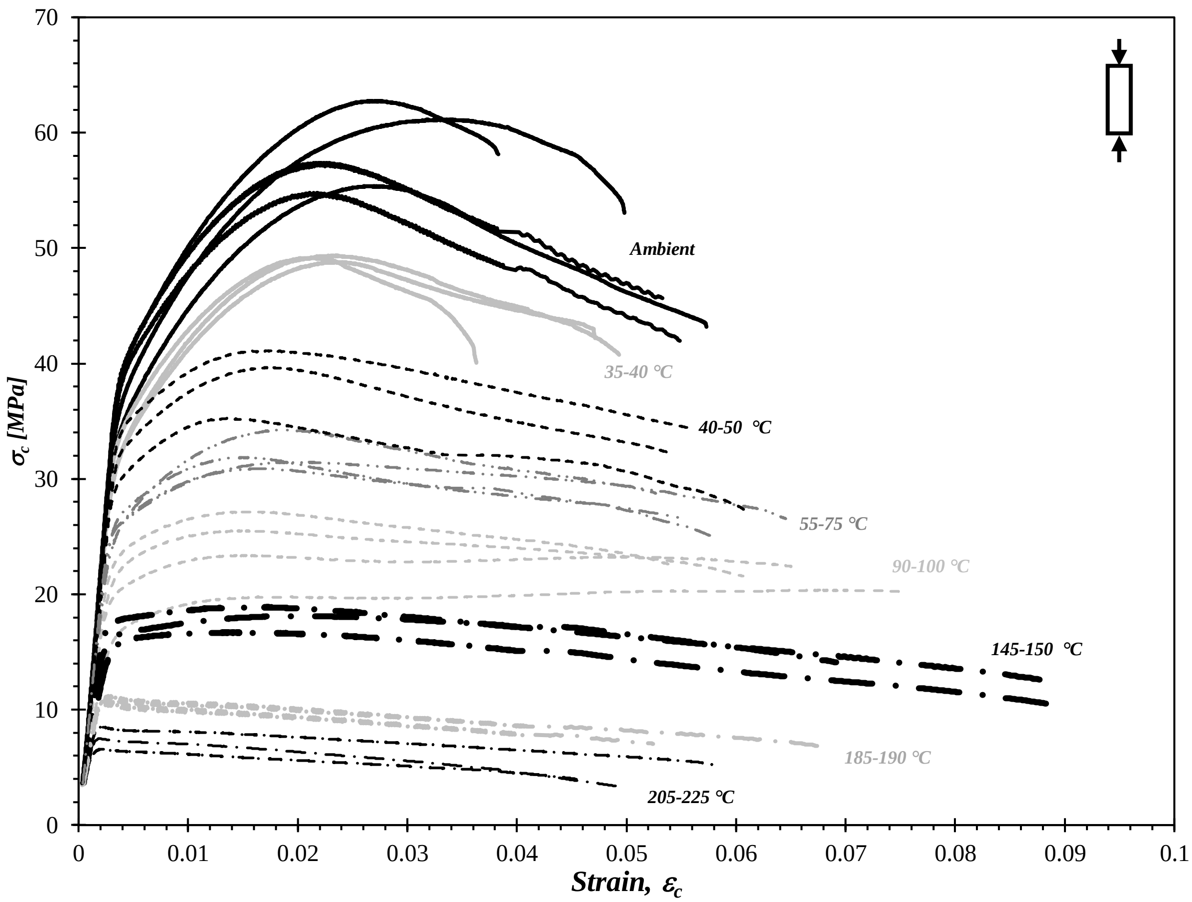

Figure 4. Stress-strain curves of bamboo in compression at elevated temperatures.

Figure 5. Laminated bamboo failure modes at different temperatures in compression.

Figure 5 displays photos of specimens after being tested in compression. The failure mechanism for specimens tested in compression at ambient temperature is associated to crushing failure; cracks along the sample's longitudinal axis and crushing in the upper and bottom parts are usually observed. At temperatures between 60 and 150°C, larger plastic deformation is observed and specimens show some buckling due softening of the bamboo matrix. For temperatures above 150°C (onset of pyrolysis), the failure mechanism is governed by plastic buckling failure produced by geometrical instability induced by the reduction in the stiffness, with a constant decay in the stress-strain curve after the maximum compressive stress has been reached.

4.1.2 Compressive Strength

Based on results from 11 tests, the average compressive strength of bamboo at ambient temperature was measured to be at 51.7 MPa (SD = 5.6 MPa). A total number of 63 specimens were tested to obtain the reduction in the absolute compressive strength as a function of temperature, as presented in Figure 6(a). Bamboo suffers a decrease in its compressive strength for temperatures between ambient and 100°C. Between 100 and 150°C, there is no apparent reduction, but above 150°C, the reduction continues until the compressive strength is practically lost. Figure 6(b) shows the normalised values and the proposed model with a 95 % confidence interval for the compressive strength as a function of temperature based on the average strength at ambient. Equation 1 shows a model segmented in three different temperature ranges for obtaining the reduction for compressive strength of bamboo at elevated temperatures.

$$\frac{\sigma_{c,Temp}}{\sigma_{c,amb}} = \begin{cases} -9.0 \times 10^{-3} \cdot T + 1.20 & 20°C \leq T < 100°C \\ 0.3 & 100°C \leq T < 150°C \\ -2.0 \times 10^{-3} \cdot T + 0.60 & 150°C \leq T < 250°C \end{cases} \quad (1)$$

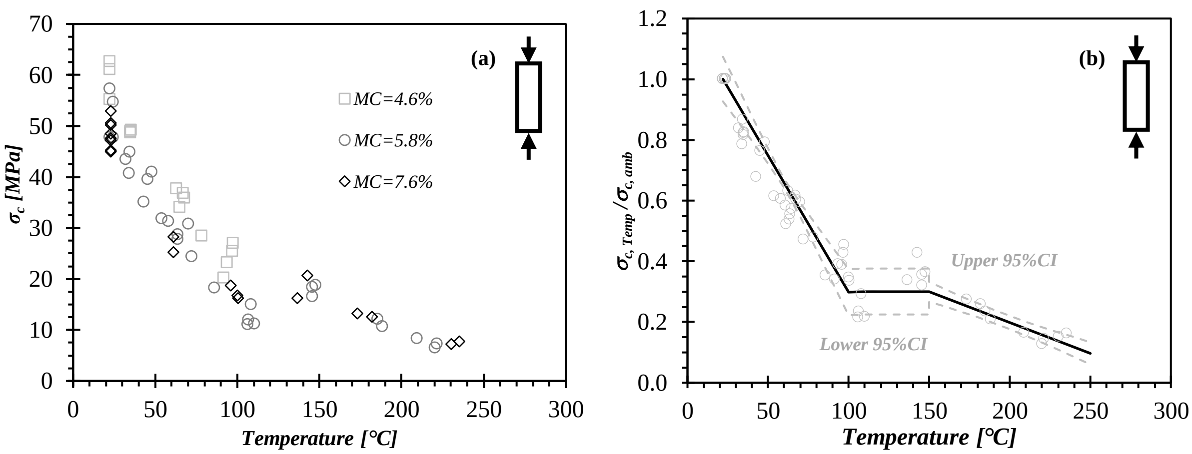

Figure 6. (a) Compressive strength and (b) normalised compressive strength for bamboo at elevated temperatures with a 95% CI.

4.1.3 Modulus of Elasticity

Figure 7(a) shows the absolute values of *MoE* in compression directly measured at ambient temperature using strain gauges. The average *MoE* at ambient temperature for bamboo in compression is 10,429 MPa (based on the average of four tests with an SD=193 MPa). *MoE* in compression was obtained indirectly for 21 specimens tested at elevated temperatures, according to the experimental procedure explained in Section 3.2. Tests results show that *MoE* in compression decreases linearly as a function of temperature, as presented in Figure 7(a). Figure 7(b) shows the normalised values of *MoE*; based on average *MoE* in compression at ambient. The results on the elasticity have a higher scatter than those found for strength tests. Equation 2 shows a proposed model for obtaining the reduction for *MoE* in compression for bamboo at elevated temperatures, with a 95 % confidence interval.

$$\frac{E_{c,Temp}}{E_{c,amb}} = \begin{cases} -1.8 \times 10^{-3} \cdot T + 1.04 & 20°C \leq T < 150°C \\ -1.4 \times 10^{-3} \cdot T + 0.99 & 150°C \leq T < 250°C \end{cases} \tag{2}$$

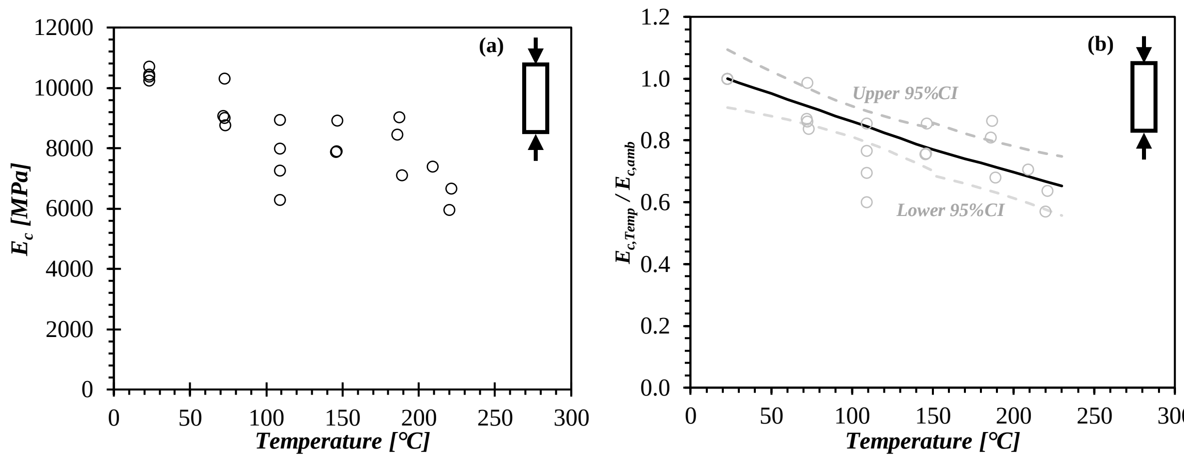

Figure 7. (a) *MoE* in compression and (b) normalised *MoE* in compression for bamboo at elevated temperatures with a 95% CI.

4.2 Tension

4.2.1 Stress-strain curves and failure mechanisms

As shown in Figure 8 and 9, bamboo tensile strength test samples experience a brittle failure mechanism at ambient and elevated temperatures with a linear-elastic behaviour until reaching the failure at the maximum strength. At elevated temperatures, there is a reduction in the tensile strength and *MoE* in tension. Figure 8 presents representative curves of tensile stress vs crosshead displacement. Figure 9 shows all tensile strength test specimens after testing; evidencing, as expected, that all test specimens failed at the node.

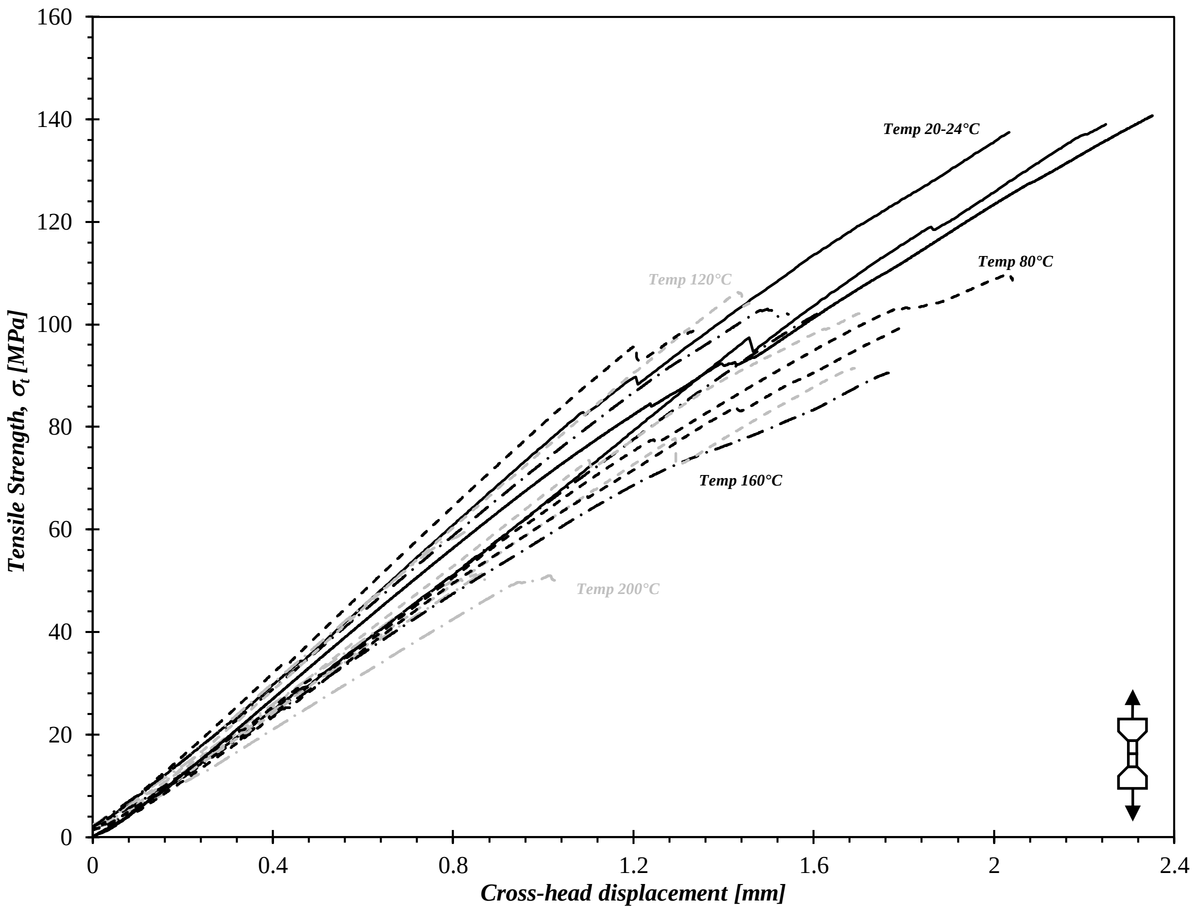

Figure 8. Stress-displacement curves of bamboo in tension at elevated temperatures.

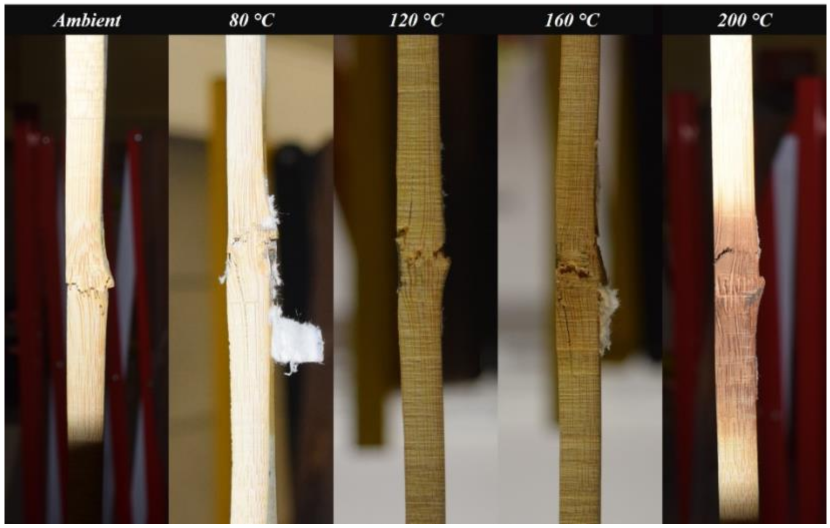

Figure 9. Bamboo failure modes at elevated temperatures in tension.

4.2.2 Tensile Strength

The average tensile strength of bamboo at ambient temperature was measured to be at 123.8 MPa (SD=13.81 MPa) based on results from nine tests. A total number of 35 specimens were tested to obtain the reduction in the absolute tensile strength as a function of temperature as presented in Figure 10 (a). Figure 10 shows that bamboo suffers a reduction in the tensile strength of about 30% at 150°C. The reduction of the tensile strength as a function of temperature is steeper for at temperatures above 150°C. Equation 3 shows a proposed model with a 95 % confidence interval for obtaining the reduction for tensile strength of bamboo at elevated temperatures. The reduction in the tensile strength is lower than the reduction in compression, and the variation in the data is also lower than for the compressive tests. All the specimens tested at different temperatures presented a linear elastic behaviour until reaching the failure. The maximum stress seems to be more consistent as the strength exclusively depends on fibre performance. It was not possible to conduct more tests above 200°C as there was a significant release of smoke and pyrolysis gases, and there was not a smoke extraction system in the room where the tests were conducted.

$$\frac{\sigma_{t,Temp}}{\sigma_{t,amb}} = \begin{cases} -2.3 \times 10^{-3} \cdot T + 1.06 & 20°C \leq T < 150°C \\ -5.8 \times 10^{-3} \cdot T + 1.58 & 150°C \leq T < 200°C \end{cases} \tag{3}$$

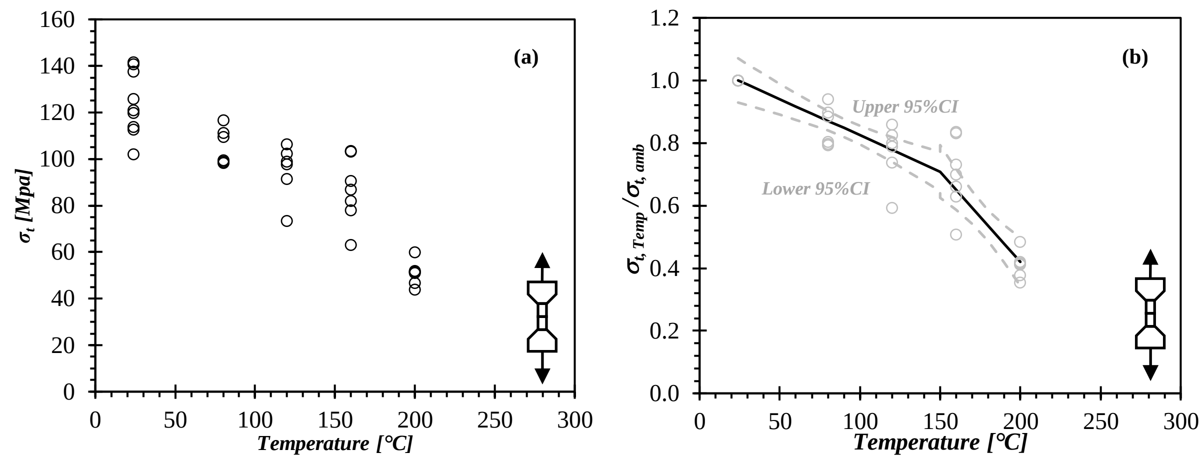

Figure 10. (a) Tensile strength and (b) normalised tensile strength for bamboo at elevated temperatures with a 95% CI.

4.2.3 *Modulus of Elasticity*

Results for the *MoE* in tension directly measured with strain gauges at ambient temperatures, as well as the results at elevated temperatures are presented in Figure 11(a). The average *MoE* at ambient temperature for a group of three bamboo specimens is 15455 MPa (SD=1341 MPa), which starts to decrease as the temperature increases according to Figure 11(a). *MoE* in tension was obtained indirectly for seventeen specimens tested at elevated temperatures, according to the experimental procedure explained in Section 3.2. Figure 11(b) shows the normalised values of *MoE* at elevated temperatures. Same as the behaviour for the compression tests, elasticity is reduced in a lower magnitude than strength. At 100°C, the reduction in *MoE* is only 5%, whereas at 200°C the reduction is about 20%. Equation 4 presents the model proposed with a 95% confidence interval to predict the normalised *MoE* of bamboo in tension.

$$\frac{E_{t,Temp}}{E_{t,amb}} = \begin{cases} -6.7 \times 10^{-4} \cdot T + 1.02 & 20°C \leq T < 150°C \\ -2.4 \times 10^{-3} \cdot T + 1.27 & 150°C \leq T < 250°C \end{cases} \quad (4)$$

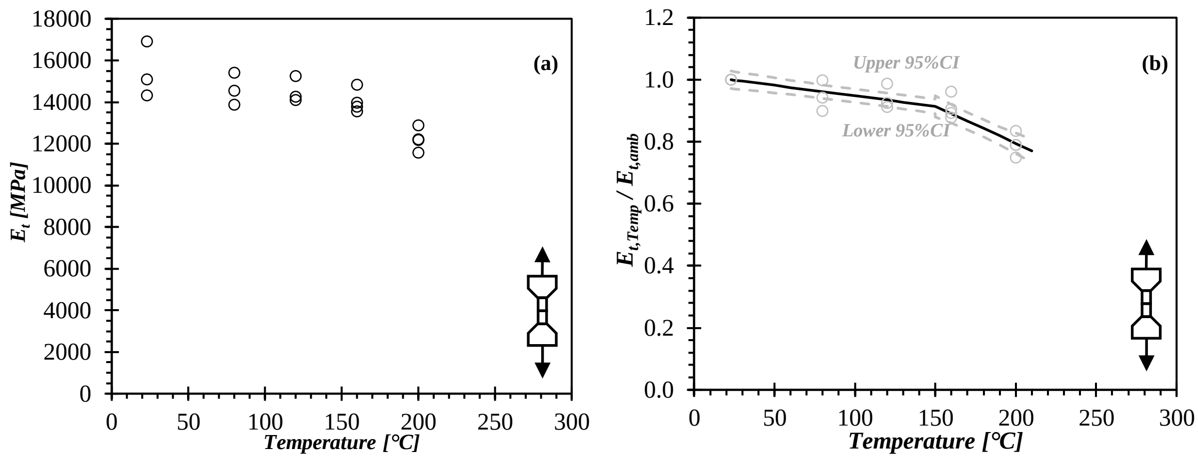

Figure 11. (a) *MoE* in tension and (b) normalised *MoE* in tension for bamboo at elevated temperatures with a 95% CI.

5 Analysis and discussion

A thermal analysis was required to understand the heat transfer in the test specimens to adequately characterised the internal temperature at the moment of mechanical failure. Figure 1 shows the evolution of the surface and internal temperatures in the test specimens. A correlation between the surface temperature and the temperature in the core was developed to describe the unavoidable gradient presented in the compressive specimens after reaching the steady-state. The heating rate for the compressive tests was determined by the heating rates that can be achieved with the environmental chamber. For the tensile tests, the times required to achieve steady-state conditions were determined by the equation of the characteristic-time based on the thermal properties of bamboo. The thermal gradients in the tensile specimens were disregarded once the characteristic-time required to achieve steady-state was overcome. The internal temperature in the samples was assumed to be equal to the surface temperature, which was captured by the thermocouple connected to the surface of the specimen.

Past studies have found that the steep reduction in the compressive strength of bamboo observed in Figures 4, 5 and 6 for temperatures around 100°C is associated with the glass transition temperature of lignin, which happens between 60 and 80°C [29, 30]. Lignin is present not only in the bamboo matrix, but bonding the fibre bundles within bamboo [31, 32]; therefore, softening of the lignin may reduce the elasticity of the matrix that allows for the fibres to work in composite action [22].

Based on the outcomes described in Section 4.1, bamboo experiences significant reduction in the compressive strength at temperatures as low as 40°C. The compression stress-strain curves presented in Figure 4 show a 70% increase in ultimate strain between 100 and 150°C. However, the ultimate strain of bamboo for temperatures above 150°C is similar to values observed at ambient temperature conditions. The increase in ultimate strain is thought to be associated with the matrix softening due to the glass transition of lignin or due to the fibre moisten produced by water vaporisation [33]. Steam combined with elevated temperatures is known to allowing plastic deformations commonly used to bent bamboo and timber members [30]. Steam is produced when bamboo is exposed to temperatures above 100°C and water vaporises within the cells.

The above explains the reduction in the compressive strength at elevated temperatures and the reasons why the tensile strength does not have a similar trend (refer to Section 4.1 and 4.2). The fibre bundles are the major contributors to the bamboo tensile strength and elasticity, but they are mainly composed by cellulose, which does not suffer such degradation for temperatures below

100°C [33]. That could be one of the reasons why the significant reduction in the bamboo tensile strength only occurs after the temperature is above 150°C, as it is shown in Figure 8 and 10.

As expected, a reduction in *MoE* presented in figure 7 has an influence in the compressive failure mechanism of bamboo under compression loads. A lower *MoE* will decrease the buckling capacity, and specimens that initially failed by crushing at ambient temperatures [34, 35] will undergo geometrical instability at elevated temperatures.

The stress-strain curves presented in Figure 4 evidence a shift towards a characteristic plastic buckling failure curve, rather than a perfect elastic-plastic behaviour, typical for bamboo compressive stress-strain curves at ambient temperature [34, 35]. Compressive strength test specimens within the scope of this study were prepared with a slenderness ratio of 1:6. That aspect ratio ensures a crushing failure at ambient temperature conditions, as suggested in the European standard adopted to conduct such a tests [26]. However, the reduction in *MoE* at elevated temperatures (above 150°C) contributes for the compressive strength test specimens to fail in a type of buckling (refer to Figure 5). The specimens suffer a significant reduction in the stiffness when the temperature is above the onset of pyrolysis, approximately 150°C [19], and this led to a geometrical instability that significantly reduces the bamboo compressive strength. Although some delamination is observed in the specimens presented in Figure 5, those fissures appear after the maximum compressive stress is reached, and they are not responsible for the collapse of the specimens. Previous researchers have found that Phenol Resorcinol Formaldehyde (PRF) has demonstrated excellent performance at elevated temperatures [16, 36], and this was confirmed during the experiments, as the laminated bamboo samples did show evidence of delamination.

Figure 12 compares the outcomes of the current study against compressive strength and *MoE* reduction in compression against previous studies [22, 23]. As it can be noticed, the reduction in compressive strength of bamboo and timber are very similar [37]. Past studies have shown that bamboo and timber strength tend to increase or remain constant for temperatures between 100 and 140°C [33, 38, 39]. Experimental studies on pre-dried timber specimens have shown that the strength increase at this temperature range does not follow the same trend, and the strength shows a continuous reduction [33, 40]. Therefore, it can be inferred that the compressive strength rise in that range is influenced by the initial moisture content of the material before heating, which is not within the scope of the current study.

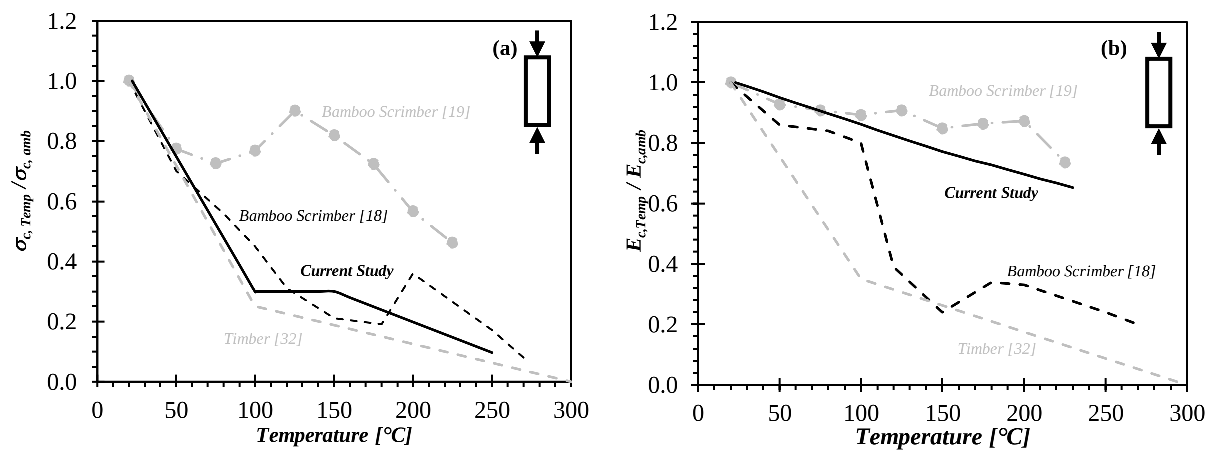

Figure 12. (a) Normalised compressive strength and (b) and *MoE* in compression of bamboo at elevated temperatures.

Figure 13(a) compares the reduction in the tensile strength of bamboo against prior studies conducted in timber and bamboo [22, 23, 37]. Noticeably, the reduction in tensile strength is lower than in compression. Figure 13(b) shows a similar comparison for *MoE* of bamboo in tension. Same as in compression, when compared to timber, more of the *MoE* of bamboo is retained at elevated temperature [37]. These tests were conducted up to 200°C, and the proposed model for the tensile strength and *MoE* in tension should be limited to this temperature range.

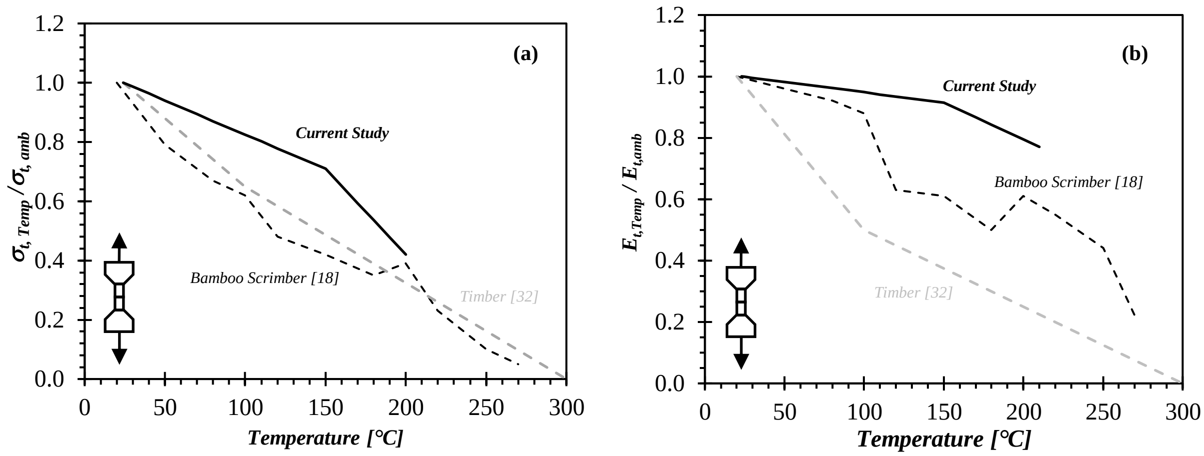

Figure 13. (a) Normalised tensile strength and (b) and *MoE* in tension of bamboo at elevated temperatures.

To the best of the authors' knowledge, this is one of the first studies aimed at understanding the mechanical behaviour of round and laminated bamboo at elevated temperatures. The reduction factors for strength and stiffness presented in this study offer valuable information which can derive in significant progress for bamboo's construction industry, similar to what has been reported already for timber (Buchanan, 2000). The results presented herein can be used to elaborate on the constitutive stress-strain models of bamboo in compression and tension. The compressive, tensile and bending capacity of load-bearing bamboo members exposed to fire can be accurately predicted if these factors are used to develop thermo-mechanical models based on the axial stress-strain relationships of bamboo at elevated temperatures (Buchanan, 1990; Zaw, Mohamed, Saleh, & Bakar, 2005).

The outcomes of these tests can also be adopted to design bamboo structures where the design room temperature can go up to 50 or 60°C. These equations can be implemented in structural design guidelines or bamboo constructions codes that include strength and *MoE* reduction factors due to temperature effects.

6 Conclusions

Conventional engineering methods based on the reduced cross-section conceived for timber cannot be applied for bamboo structures until the first principles behind these methods are validated for bamboo. Stress-strain constitutive models for bamboo at elevated temperatures are crucial to enable the performance-based design bamboo structures.

The outcomes of the experimental study described herein are clear in demonstrating the mechanical behaviour of bamboo at elevated temperatures. The derived models yield the following conclusions:

- When compared to timber, bamboo experiences a similar reduction in compressive strength but a significantly lesser reduction in tensile strength. When comparing the reduction in *MoE*, bamboo retains a significantly higher amount for both the compressive and tensile stress states.
- At 200°C, bamboo retains 20% of the compressive strength and 70% of *MoE* in compression in relation to the measurements at ambient temperature conditions; and
- At 200°C, bamboo retains 42% of the tensile strength and 79% of *MoE* in tension in relation to the measurements at ambient temperature conditions.

The reduction in the mechanical properties of bamboo at elevated temperatures has a significant impact on the failure mechanisms and the stress-strain curves. This becomes even more detrimental for temperatures above the onset of pyrolysis (around 150°C). Outcomes from this study can be used to obtain stress-strain constitutive models for bamboo at elevated temperatures. Further research studies should focus on producing the abovementioned constitutive models and on validating them against full-scale experimental tests of load-bearing bamboo members under different heating scenarios.

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Figure captions

Figure 1. (a) Temperature on the surface and in the centre of compressive specimens at 120°C. The rate of internal temperature change against time to exposure is presented in the secondary axis. (b) Temperature on the surface and in the centre of specimens at the steady-state condition.

Figure 2. (a) Test setup and specimen dimensions for performing compressive strength tests (b) and tensile strength tests on bamboo at elevated temperatures.

Figure 3. Stress-strain elastic curves to obtain the *MoE* at ambient and elevated temperatures.

Figure 4. Stress-strain curves of bamboo in compression at elevated temperatures.

Figure 5. Laminated bamboo failure modes at different temperatures in compression.

Figure 6. (a) Compressive strength and (b) normalised compressive strength for bamboo at elevated temperatures.

Figure 7. (a) *MoE* in compression and (b) normalised *MoE* in compression for bamboo at elevated temperatures.

Figure 8. Stress-displacement curves of bamboo in tension at elevated temperatures.

Figure 9. Bamboo failure modes at elevated temperatures in tension.

Figure 10. (a) Tensile strength and (b) normalised tensile strength for bamboo at elevated temperatures.

Figure 11. (a) *MoE* in tension and (b) normalised *MoE* in tension for bamboo at elevated temperatures.

Figure 12. (a) Normalised compressive strength and (b) and *MoE* in compression of bamboo at elevated temperatures.

Figure 13. (a) Normalised tensile strength and (b) and *MoE* in tension of bamboo at elevated temperatures.