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ALTERNATIVE STRUCTURAL FIRE MODEL FOR PREDICTING BENDING CAPACITY IN LAMINATED BAMBOO BEAMS AND CROSS-LAMINATED TIMBER (CLT) HARDWOOD PANELS

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ABSTRACT: Bamboo and hardwood cross-laminated timber (CLT) products have a limited understanding of their structural fire performance, restricting their use as a primary load-bearing material. To tackle these limitations, an analytical structural model has been developed to assess the bending capacity of laminated bamboo beams and CLT hardwood panels when exposed to fire conditions. This paper studies the constitutive elastoplastic models for laminated bamboo and hardwood CLT at high temperatures. Utilising stress-strain models, the mechanical response of these materials in both compression and tension is described. The proposed beam structural model combines these constitutive models with time-dependent temperature gradients and the strength and stiffness reduction factors for bamboo and hardwood. This approach aims to improve the prediction of stress profiles, strain profiles, and flexural capacity during fire exposure, providing an alternative to traditional methods that rely on charring rates.

KEYWORDS: Laminated bamboo, hardwood CLT, stress-strain model, fire behaviour, section analysis.

1 – INTRODUCTION

Although modern guides for designing fire-safe mass timber structures [1,2] include constitutive models for characterising the thermal and mechanical response of laminated softwood, limited data are available for modelling mass timber made of hardwood species or alternatives like laminated bamboo.

Several authors have highlighted the need for a different approach to calculating the thermomechanical response of charring materials during fire, such as laminated bamboo or Cross-Laminated Timber (CLT) [3-5].

Although charring rates obtained from standard furnace tests and the reduced cross-section method have traditionally been used to calculate the bending capacity of structural timber members exposed to fire, this method is limited to the exact conditions under which the charring rates were determined. Some limitations of this method include varied thermal exposures, such as exposure to lower heat fluxes or even modelling the performance of the element during the decay phase of the fire [6,7]. If the charring rates used in the model are inaccurate, the reduced cross-section method may overestimate the beams' capacity. An alternative approach that relies on the internal temperature profile could be beneficial when obtaining reliable charring rates is challenging or when there is limited information about the material's properties.

The approach proposed in this paper uses constitutive stress-strain models to describe the mechanical response of bamboo and hardwood in compression and tension. The models describe the elastoplastic response of both bamboo and hardwood in bending. To simplify the calculations, a bi-linear model was assumed to represent the compression response of both materials. Then, the beam structural model combines the constitutive models with time-dependent temperature gradients along the cross-section and the strength and stiffness reduction factors for bamboo and hardwood at high temperatures to describe the beam mechanical response over time.

The model considers the progressive loss of strength and stiffness behind the char layer due to elevated temperature while accounting for the non-elastic behaviour of these materials [5,8]. Another critical assumption relies on the continuity of the material along the glue lines, as the composite action could be maintained until the failure in the fibres was reached, and no char fall-off or delamination was considered in the analytical model [8].

The proposed structural model can predict the stress and strain profiles and the flexural capacity of members in bending before and during fire exposure for both bamboo and hardwood elements. The model results have been compared against experimental tests performed on laminated bamboo beams at The University of

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Queensland and hardwood CLT panels (or slabs) at an accredited fire resistance furnace in Australia.

This model provides an alternative approach to predicting the bending capacity of materials like bamboo and hardwood CLT, particularly when there is limited knowledge about the materials' charring rates or when the thermal or fire exposure differs from those used to calculate the standard charring rates. The models also present an alternative for fire decay, where the loss of strength is not necessarily linked to char progression but rather to heating the material behind the char depth.

2 – MATERIALS AND TEST METHODS

2.1 MATERIALS

2.1.1 Laminated bamboo beams

The laminated bamboo beams for these fire tests were made from *Phyllostachys edulis* bamboo species and phenol-formaldehyde ad. The beams had an average density of 691 kg/m^3 (SD = 23.2 kg/m^3) and a moisture content of 6%. Dimensions were 46 mm wide, 94 mm deep and 1900 mm long. Table 1 and Figure 1 present the mechanical properties and stress-strain model describing the bamboo beam's behaviour in compression and tension at ambient temperature.

2.1.2 Hardwood CLT panels

The CLT panels were made of Australian *Eucalyptus nitens* (E. nitens) hardwood and non-heat-resistant 1C-PUR glue. They were 175 mm and 225 mm thick (equivalent to 7 and 9 layers of 25 mm each). Their average density was 607 and 590 kg/m^3, respectively, with an average moisture content of 7.4%. They were 2950 mm wide and 4325 mm long. The mechanical properties and the perfect elastoplastic model used to describe E. nitens behaviour in compression and tension are presented in the table and Figure 1.

Table 1: Material properties.

	Laminated Bamboo	Cross Laminated Timber
Species	*Phyllostachys edulis*	*Eucalyptus nitens*
Average density, ρ [kg/m^3]	691.0	598.5
Compressive strength, σ_c [MPa]	51.7	25.0
Tensile strength, σ_t [MPa]	63.6	24.0
Modulus of elasticity, E [MPa]	10,429.0	13,000.0

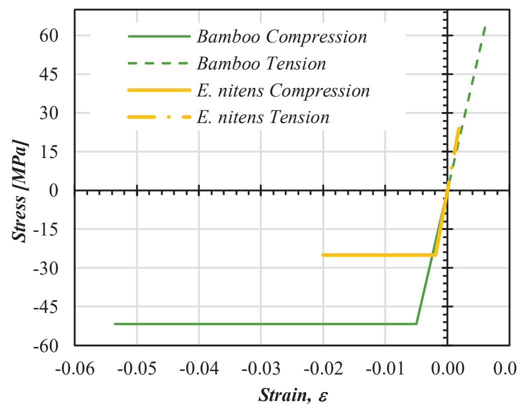

Figure 1. Constitutive stress-strain model for laminated bamboo and timber at ambient temperature.

2.2 EXPERIMENTAL TEST SETUP

2.2.1 Bending fire tests in laminated bamboo

The laminated bamboo beams were loaded in 4-point bending with a constant load and then exposed to a constant heat flux of 60kW/m^2 applied with gas-fueled radiant panels until reaching failure. The beam was only burnt in the middle third of the span where the bending moment is maximum. A constant force of 4, 6 and 8 kN (27%, 40% and 53% of the failure load) was applied to the beam. Strain gauges and a Digital Image Correlation (DIC) system were used to measure the strain along the cross-section. Figure 2 presents the setup developed for the fire bending tests.

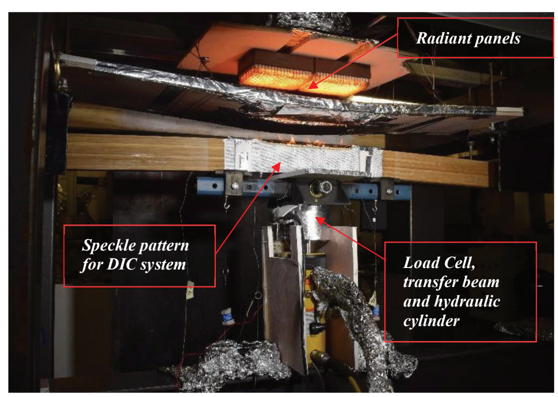

Figure 2. Experimental set-up for the bending tests performed under simultaneous load and fire exposure in laminated bamboo.

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2.2.2 Standard fire tests in CLT

Two CLT panels, measuring 175 mm and 225 mm in thickness, were tested in a standard furnace under bending loads, with a uniformly distributed load applied by Australian Standard AS 1530.4:2014. The panels were subjected to uniform loads of 4 and 8 KPa, respectively. Additional thermocouples and sensors were installed in the panels to assess char depth, heated sections, and deflections. Figure 3 presents the test setup for the structural fire tests on the CLT panels.

Figure 3. Experimental set-up for the standard fire tests as per AS 1530.4:2014 in CLT panels.

3 – ANALYTICAL MODEL DURING FIRE

3.1 STRENGTH AND STIFFNESS REDUCTION AT HIGH TEMPERATURES

The mechanical properties are expected to decay due to elevated temperatures. The reduction factors used in the models are those presented by Gutierrez and Maluk (2020) [9] for laminated bamboo and the factors outlined in Eurocode 5 (1995) for timber [1]. These factors enable quantifying the reduction in compressive strength, tensile strength, and modulus of elasticity, along with their corresponding effects in the constitutive stress-strain models for temperatures ranging from ambient up to 250°C and 300°C for bamboo and timber, respectively. Beyond 250°C and 300°C, the materials become thoroughly charred, and their mechanical properties are assumed to be zero, as they cannot support any load. Figure 4 illustrates the reduction in mechanical properties of both bamboo and timber at elevated temperatures.

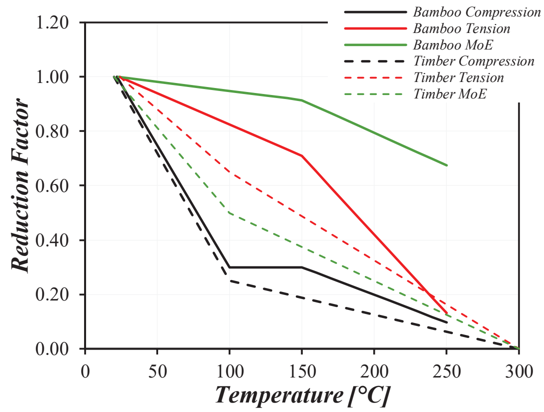

Figure 4. Strength and modulus of elasticity (MoE) reductions with temperature for bamboo and timber.

3.2 FIRE STRUCTURAL MODEL

The proposed structural model is founded on a fibre section analysis that utilises the compressive and tensile stress-strain relationships of bamboo and timber outlined in the prior section. The fibre section analysis keeps equilibrium in the cross-section by determining the bending capacity while considering variations in strength and stiffness due to high temperatures. To analyse the section using beam theory [10] the model depends on the following assumptions:

- The strain is distributed linearly along the cross-section until failure. Therefore, plane sections remain plane during and after bending (Euler-Bernoulli theory).
- As mentioned earlier, the compressive stress distribution across the beam is linear-elastic until the compressive yielding point is reached. Beyond this point, the material exhibits perfect elastic-plastic behaviour. The tensile stress distribution is considered linear-elastic until failure occurs. Generally, bamboo and timber exhibit greater tension strength than compression, making the failure on the tension side the prevailing cause for the beam's failure.
- The adhesive performs reliably at high temperatures and does not fail before the bamboo or timber fibres. As a result, the bamboo or timber laminates remain perfectly bonded, and the analysis does not consider delamination.
- While the beam consists of various layers, the mechanical properties of its cross-section can be regarded as homogenous. The sole factor that might justify reducing these mechanical properties is temperature change.
- The bending stress is determined by the strain and temperature in each fibre. Discretising the cross-section makes calculating the equilibrium condition easier. Failure occurs when the maximum strain in

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the outermost fibre is reached. An optimisation function maximises the resultant bending moment by adjusting the location of the neutral axis.

The model requires understanding the geometrical properties, detailed temperature profiles, and a reduction of mechanical properties in each fibre and time step (t_i). The temperature profiles at each time ($T_{y,i}$) can be obtained through numerical modelling of the heat transfer in the structural elements or via experimental testing by measuring the temperature gradients in the beams or panels after exposure to the same thermal boundary conditions. In this case, the temperature profiles were obtained through experimental data captured with in-depth thermocouples.

Once the temperature distribution is known, the reduction of the mechanical properties is calculated from the constitutive stress-strain models and the reduction factors at the elevated temperature presented above.

Once the mechanical properties for each time step (t_i) have been estimated, beam theory and section analysis are used to calculate the strain (ε_i) at each fibre based on the strain at the top or bottom fibre of the beam. With the strain at each fibre known, the normal bending stress ($\sigma_{y,i}$) and the equivalent internal force (F_i) can be determined, provided the summation of horizontal forces remains zero ($\Sigma F_i=0$).

The resultant internal bending moment (M) in the cross-section can be calculated as the sum of the internal moments at each layer, equivalent to the internal force in each layer (F_i) multiplied by the lever arm (y_i), as shown in Figure 5.

Figure 5 summarises the analysis conducted to obtain the stress and strain profiles and the internal bending moment in the beams when exposed to fire and elevated temperatures.

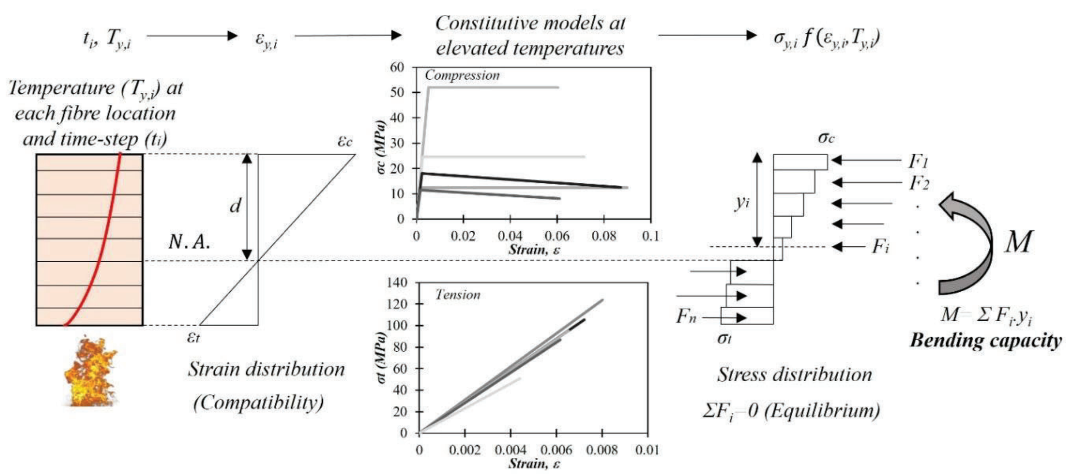

Figure 5. Summary of the calculation of the internal bending moment for the proposed structural fire model

4 – RESULTS AND ANALYSIS

4.1 LAMINATED BAMBOO

4.1.1 Temperature Profiles

The temperature profiles were obtained from specimens subjected to an incident radiant heat flux of approximately 60 kW/m², replicating the thermal exposure experienced by the beams used in the fire bending experiments. Eight thermocouples were arranged across the beams' cross-section at depths measured from the exposed side: 3 mm, 8 mm, 15 mm, 25 mm, 40 mm, 60 mm, 80 mm, and 94 mm. For the numerical model, the cross-section was segmented into sections of 1 mm depth. Temperatures were linearly interpolated every mm based on the measurements taken at the specified locations. Figure 6 illustrates the temperature profiles in the cross-section for different exposure durations, with marks indicating the thermocouple locations.

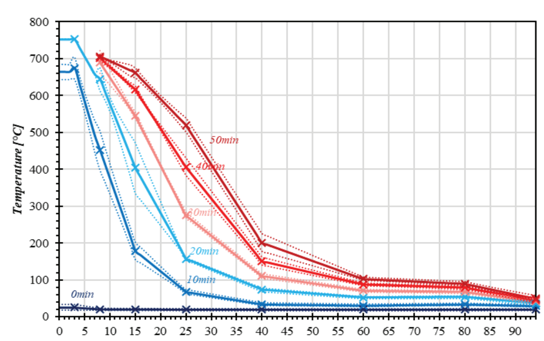

Figure 6. Average temperature profiles (and Standard deviation) at different times of exposure

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4.1.2 Strain and stress distribution

The model for the laminated bamboo beams allows for the calculation of strain and stress profiles under various loading conditions after any exposure duration, provided the beam's temperature profile is known. Figure 7 illustrates the (a) strain and (b) stress profiles in the laminated bamboo beams under three different loading conditions during four-point bending at 4, 6, and 8 kN, just before the beam is exposed to fire. The results show the greater the load, the greater the strain and stress experienced by the bamboo fibres.

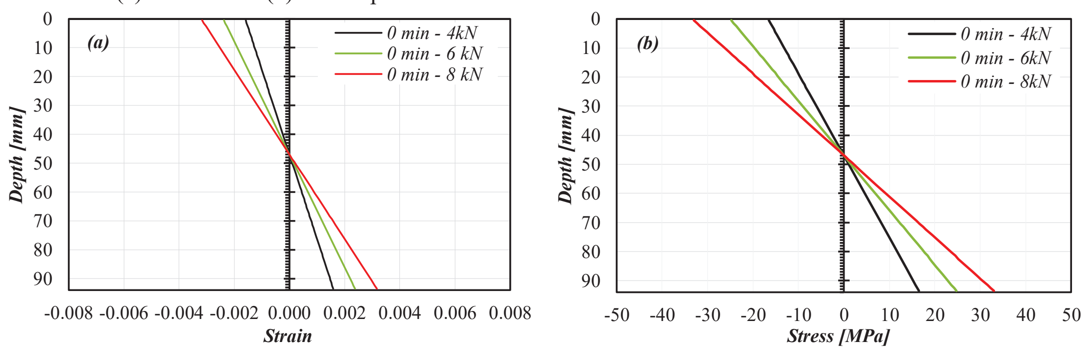

Figure 7. Stress (a) and strain (b) profiles for the bamboo beam just before fire exposure.

Figure 8 shows the strain profiles in the beams after 0 and 5 minutes of exposure in beams loaded with 4, 6 and 8 kN. The graph demonstrates how the strain in the beam increases due to the reduction in cross-section and the progression of the charring front. This also results in a shift of the neutral axis. Before the fire, the neutral axis was positioned at the mid-height of the cross-section (47 mm) for all loading conditions. However, as the charring front progresses and internal temperatures rise behind it, the fibres experience a reduction in their mechanical properties, resulting in a reduced section available to bear the loads. This increase in strain and stress in the beam causes the neutral axis to shift.

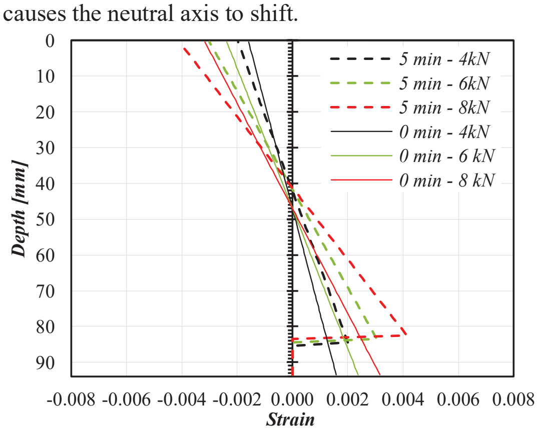

Figure 8. Strain distribution for the bamboo beams after 0 and 5 minutes of fire exposure.

4.1.3 Laminated bamboo fire test results

Thanks to the DIC system results, the strain profiles in the beam were measured with high accuracy. Figure 9 presents images of the strain in the beams captured with the DIC system in a beam loaded with 8kN before and after the fire.

Figure 10 presents the experimental results of the strain profile in the beams measured after 5 minutes of fire exposure. These results are compared with the strain profiles obtained from the analytical model. The findings demonstrate a strong agreement between the model and the experimental results, accurately displaying the progression of the charred front.

The strain in the model is generally lower than the experimental strain captured by the DIC. However, this could be associated with underestimating the actual temperature in the cross-section due to the position of the thermocouples used in the tests [11, 12]. The location of the neutral axis is consistent in both numerical and theoretical results.

The bending capacity of beams is determined by the maximum resultant bending moment developed after the mechanical properties of the beam have been affected due to increased temperatures. The strain and stresses continue to rise until the fibres in tension fail. The experimental results for beams loaded at 8, 6, and 4 kN show that the beams failed after 8.2, 16.5, and 22.6 minutes of fire exposure, respectively.

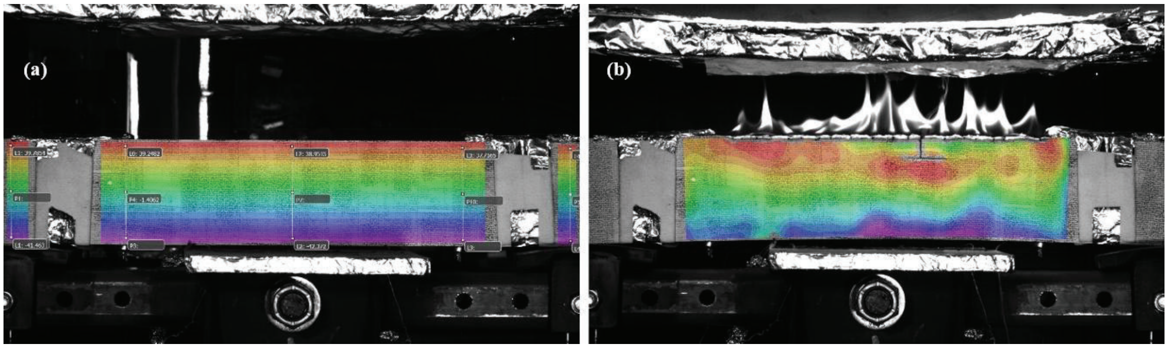

Figure 9. Strain distribution measured with the DIC system in a laminated bamboo beam loaded with 8kN before and after fire exposure.

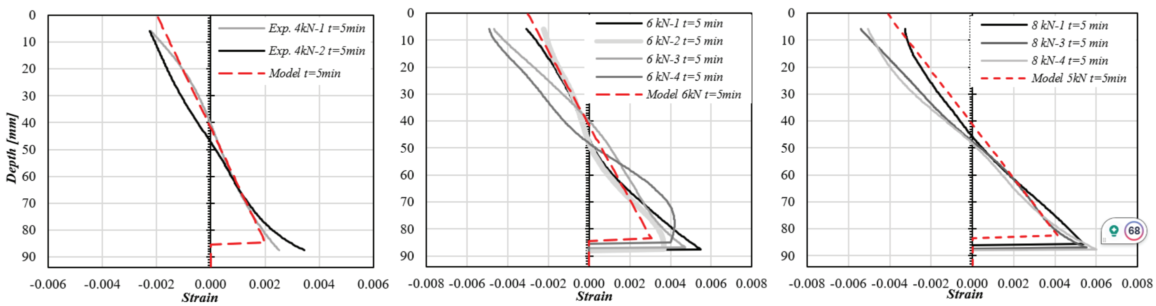

Figure 10. Strain distribution for the bamboo beams after 5 minutes of fire exposure obtained through DIC and analytical model.

Figure 11 compares the reduction in bending capacity of the beams over time, as obtained through the model and the experimental results. For the beam loaded to 8 kN, the results from the numerical model and the experimental tests differ by only 0.2% in the average time to failure. For the beams loaded to 6 and 4 kN, the variation in times to failure is approximately 11% and 12%, respectively. The standard deviation of the times to failure is also shown in Figure 11. The model presents a good agreement to predict the bending capacity of bamboo beams while describing the strain and stress distribution in the beams.

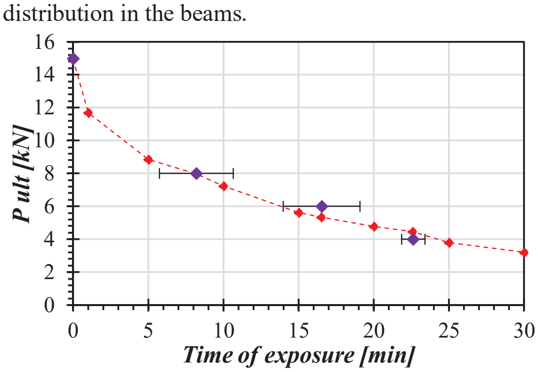

Figure 11. Bending failure load against time of exposure obtained from the analytical model.

4.2 CLT PANELS

4.2.1 Temperature Profiles

The temperature profiles were obtained from small-scale specimens subjected to an equivalent incident heat flux from standard furnace tests. Three tests were conducted on panels measuring 125 mm thickness (5 layers). In-depth thermocouples were installed in the panels at various depths. For the numerical model, the panels' cross-section was divided into segments of 1 mm depth. Temperatures were linearly interpolated every mm based on measurements taken at the specified locations. The results from these tests were utilised to extrapolate the in-depth temperatures of panels measuring 175 mm and 225 mm. Figure 12 illustrates the temperature profiles used in the models after 90 minutes of fire exposure for the 175 mm and 225 mm panels.

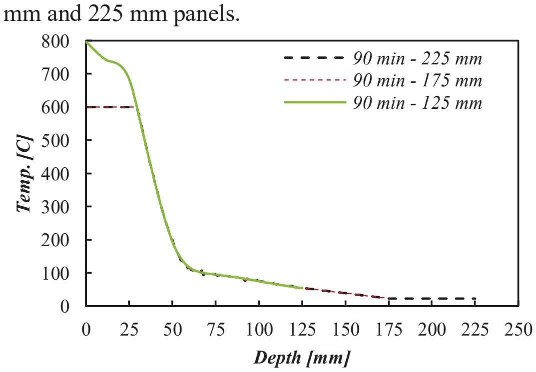

Figure 12. Temperature profiles in CLT after 90 min of fire exposure.

4.2.2 Strain and stress distribution

Once the panel temperature distribution is known, the structural model is applied to the CLT panels to calculate both panels' strain and stress profiles after a 90-minute fire. Figure 13 shows the strain and stress profiles in the two CLT panels: the 175 mm thickness loaded with 4

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kPa, and the 225 mm panel loaded with 8 kPa after 0 and 90 minutes of fire exposure.

The results demonstrate how the strain in the panels increases due to the reduction in cross-section and the progression of the charred front. The plots in Figure 13 illustrate how the decrease in mechanical properties affects the internal stresses in the heated section. The model also reveals that the crossed layers in the panels do not experience any normal stresses. The longitudinal layers are the only ones bearing the bending stress in the panels, consequently, while a significant portion of the panel is under tension, not all the cross-sections in tension support the normal stress, as only the longitudinal layers contribute to the bending capacity of the panels.

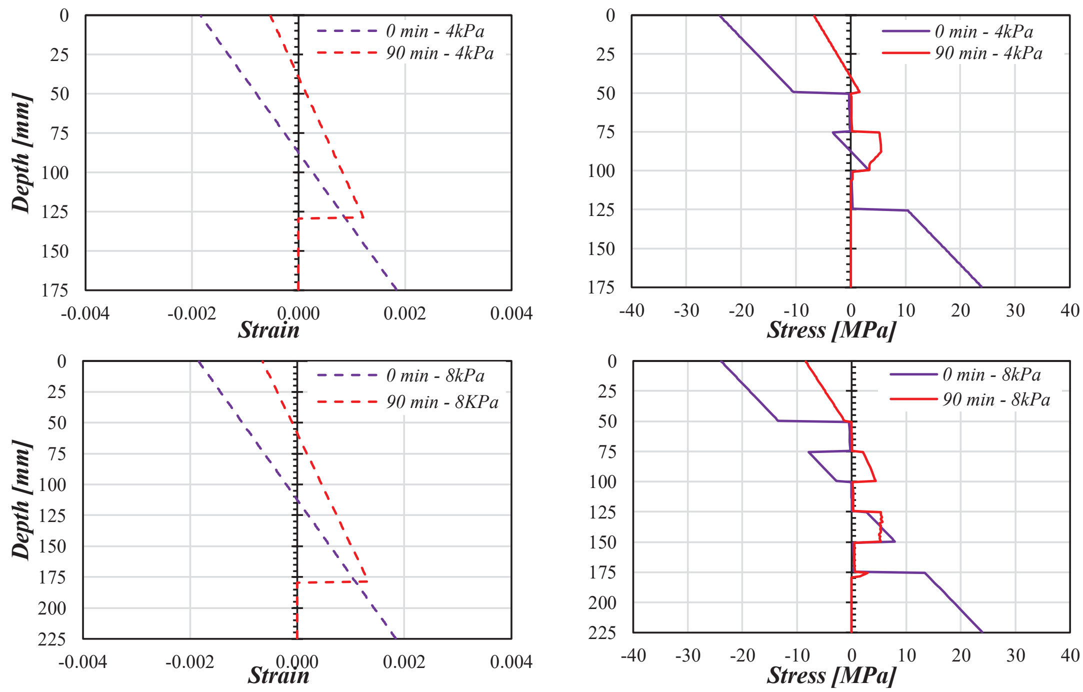

Figure 13. Strain and stress profiles for CLT panels before and after a 90-minutes fire.

4.2.3 Hardwood CLT fire test results

Similarly to the bamboo beams, the model is also used to predict the bending capacity of the panels. Before exposure to fire, the bending capacity of the 175 mm and 225 mm thickness panels is 113.5 and 175.9 kN.m, respectively. Using the previously presented temperature profiles, the calculated bending capacity of the panels after 90 minutes of fire exposure in the furnace tests is 9.9 and 25.4 kN.m, respectively. If the bending moment capacity is transformed to a uniformly distributed load, the panels can withstand a uniform load of 4.9 and 12.7 kPa, respectively. This indicates that after 90 minutes of exposure, the panels would support the imposed loads of 4.0 and 8.0 kPa, respectively, which were the selected loads for conducting the fire tests with a duration of 90 minutes.

Effectively, after conducting the structural fire tests according to Australian Standard AS 1530.4:2014, the panels did not reach failure after 90 minutes of exposure. They continued to be burned and tested for approximately 121 minutes without exhibiting structural failure.

Using the alternative structural model allowed for a safer prediction of the panels' bending capacity, which enabled a fire resistance level (FRL) of 120 minutes (REI-120) and demonstrated that the alternative model could successfully predict the bending capacity of hardwood CLT slabs.

Although the bamboo beams did not experience char fall-off, CLT cannot achieve this because the panels were manufactured with a non heat-resistant adhesive. The adhesive used to manufacture CLT panels may cause char fall-off. However, this condition can be described in the temperature profiles, as temperatures rise when new virgin timber is exposed to fire, which impacts the reduction of mechanical properties in the heated area.

5 – CONCLUSIONS

This paper provides integrated thermal and mechanical constitutive models for laminated bamboo and hardwood CLT. The proposed analytical model merges thermal and mechanical properties to predict the bending capacity, stress, and strain profiles of laminated bamboo beams and/or hardwood CLT panels in any fire scenario. This approach provides an alternative method for assessing charring load-bearing members during a fire.

Unlike traditional frameworks, like the reduced cross-section method, this approach can account for the reduction in mechanical properties and elastoplastic behaviour in compression, offering a more precise, accurate, and alternative solution for analysing the structural fire performance of materials such as hardwood timber and bamboo.

This method can address char fall-off by considering cross-section temperature profiles. It improves upon traditional frameworks, such as the reduced cross-section method, by accounting for mechanical property reduction and elastoplastic behaviour in compression, providing a precise and accurate solution for evaluating the structural fire performance of materials like hardwood and bamboo. Future work may involve using more advanced stress-strain models like the tri-linear model to evaluate bending capacity and stress-strain profiles. Other methods could reduce layer sizes or assess multiple time steps for greater accuracy in the numerical solution.

6 - ACKNOWLEDGEMENTS

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