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Modelling of Elevated Temperature Performance of Adhesives Used in Cross Laminated Timber: An Application of ANSYS Mechanical 2020 R1 Structural Analysis Software

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Abstract: There is difficulty in accurately modelling adhesive influence in structural performance of cross laminated timber (CLT), due to a lack of available knowledge on the heat performance of adhesives. Therefore, the main aim of this research was to evaluate the thermal and mechanical properties of adhesives used in production of engineered wood products like CLT. The properties of the timber species and the adhesive types used in the simulation were derived from published literature and handbooks. ANSYS mechanical 2020 R1 was employed because it has a provision for inserting the thermal condition and the temperature of the system set to the required one for analysis. The simulations were conducted for temperatures 20, 100, 140, 180, 220 and 260 °C, within which Zelinka et al conducted their experiments, which have been the basis for the current study. The main findings were, the adhesive layer had little influence on the thermal properties of CLT composite (solid wood had the same thermal properties as CLT), but had a significant effect on the structural properties of CLT composite, the stresses and strains of the simulated wood species reduced with increase in temperature, the adhesives strengths at room temperature were greater than for solid wood at the same temperature and finally, the stresses and strains of the simulated wood adhesives reduced with increase in temperature. It is also important to note that computations for temperature distribution from the char layer were lower than computed using heat transfer equation, and the simulated values from steady state model. All in all, the objectives of this research were met and more research in thermal structural modelling using ANSYS should be conducted in the future.

Keywords: ANSYS; Wood; Adhesives; Cross Laminated Timber and Thermal Structural Properties

1. Introduction

Wood adhesives are widely used in the European timber industry to tightly bond pieces of wood together, during the manufacture of cross laminated timber (CLT). There has been an increase in the use of CLT (from about 610,000 m^3 in 2015 [1] to 821,270 m^3 in 2019 [2] in Europe) as a structural material in the construction industry, both in Europe and all over the world [3]. Also, a noticeable increase in the use of CLT in building construction in the last decade has been reported, especially in Europe as a sustainable material and is used in the construction of residential buildings, educational institutions, government or public buildings and commercial spaces. CLT is used for producing wall panels, flooring panels, roofing slabs, and so on [2,3]. CLT is slowly being adopted in the UK's construction industry though its production has not yet fully kicked off. Therefore, much of CLT used in the UK is imported and the greatest volume is made from Central Europe, especially in Austria, Germany, and Switzerland [2]. In European region, the green building movement which requires constructors to use sustainable and eco-friendly construction materials has increased the demand for CLT. The concept of sustainability of timber buildings is further supported by Guo et al 2017 [4] who determined that the carbon emissions of CLT buildings are 13.2% lower than those of reinforced concrete buildings. Because timber is combustible, this has made it hard for its adoption in complex construction projects. Given that, structural fire performance of timber is one of the criterion used by architects in choosing construction materials, a lack of knowledge and confidence on the structural performance of timber under fire is a major factor that is limiting its full implementation in high rise buildings. This implies that adequate guidance and knowledge about the fire resistance/performance of CLT is required to guarantee that it can be exploited to its full capacity [5]. The major structural integrity problems with CLT are charring and delamination. The strength of wood is greatly influenced by moisture content, which is likely to immediately fall below 6.5 percent after a fire [6].

Most of the wood adhesives used are either, urea formaldehyde (UF), phenol formaldehyde (PF), polyurethane (PUR) and melamine urea formaldehyde (MUF) resins to produce engineered wood products [7–9]. Engineered wood products are based on using adhesives to stick various lamellas (i.e. layers) of timber together forming a composite. This concept imitates the combined use of materials for obtaining a single material that behaves as a "composite". The behavior of the material as a composite is challenged when the adhesive use reduces its capacity to transfer load between the various lamellas. This is a major challenge for assuring integrity of a timber structure during and after fire. The performance of load-bearing timber structures during and after a fire is a challenge within the context of ensuring the structural stability and integrity of a building structure. Hence, delamination can occur when the adhesive bond line fails in the CLT panel before charring, increasing on the fuel that can lead to fire regrowth [7–9].

One of the gaps identified by Wiesner [10] in his thesis was the difficulty in accurately modelling adhesive influence in structural performance of CLT, due to a lack of available knowledge on the heat performance of adhesives. Carrying out small scale tests or large-scale tests to analyze the thermal – structural properties of adhesives used in timber industry is time consuming, expensive, and risky. The advancement in engineering analysis and simulation has contributed to the development of robust tools like ANSYS Mechanical 2020 R1 for structural timber analysis. Given the fact that nowadays people have resorted to using timber in the construction of buildings (see [11] for examples), it is imperative for fire engineers, structural engineers, building engineers, etc. to be able to analyze the structural behavior of the timber buildings using computer software (ANSYS), without having to carryout experiments.

The main aim of this research was to evaluate the thermal and mechanical properties of adhesives used in the production of engineered wood products like CLT. This research specifically examined the following objectives.

1. To determine the influence of the adhesive layer on thermal behavior of CLT.
2. To model the thermal behavior of solid wood.
3. To determine the mechanical properties of wood adhesives, especially loss in the adhesive bond strength due to rise in temperature.

This research involved three wood species, Douglas Fir (DF), Southern Yellow Pine (SYP), and Spruce Pine Fir (SPF). Also, the following wood adhesives were used, Melamine Formaldehyde (MF), Phenol Resorcinol Formaldehyde (PRF), and Polyurethane (PUR). ANSYS Mechanical 2020 R1, was used since it has a provision to adjust the external and internal temperature of the component being analyzed and the material library can be edited to add the properties of the material being analyzed.

The following points were identified from the simulations conducted on ANSYS APDL; the stresses and strains of wood species decreased with increase in temperature, the stresses and strains of wood adhesives reduced with increase in temperature, and finally CLT and solid wood have similar thermal properties.

The main limitation was that there was no current archived data on the material properties used in thermal and structural analysis of timber products. Therefore, the researcher had to combine information from different sources, this may have had an influence on the accuracy of the simulated results. Also, the ANSYS engineering material's library was not up to date and requires to be reviewed.

2. Materials and Methods

2.1. Introduction and Materials' Properties

This section explains the materials, methods and procedures used in numerical and analytical modelling of thermal structural properties of glued timber panels. The results from the simulations will be compared with what Zelinka et al [7] got from his experimental studies. The tree species studied were Douglas Fir (DF), which is scientifically referred to as Pseudotsuga Menziesii, Southern Yellow Pine (SYP), whose scientific name is Pinus Taeda (for Loblolly Pine) and Spruce Pine Fir (SPF), which is also referred to as Picea Engelmanni (for Engelmann Spruce). The glue species studied were phenol resorcinol formaldehyde (PRF) adhesive, melamine-formaldehyde (MF) adhesive, and polyurethane (PUR) adhesive. The dimensions (in mm) of the specimen used by Zelinka are shown in figure 1 below (In the ANSYS geometry used in the simulation, 50.8 mm was subtracted from both sides, because it is assumed the tensile loads are applied at the holes). It is important to also note that, the engineering materials library for ANSYS 2020 R1 does not have the properties of the materials used in the experiment and therefore a thorough literature review was conducted to identify the elastic properties of the wood and wood adhesives used. See tables below (1, 2 & 3) for details.

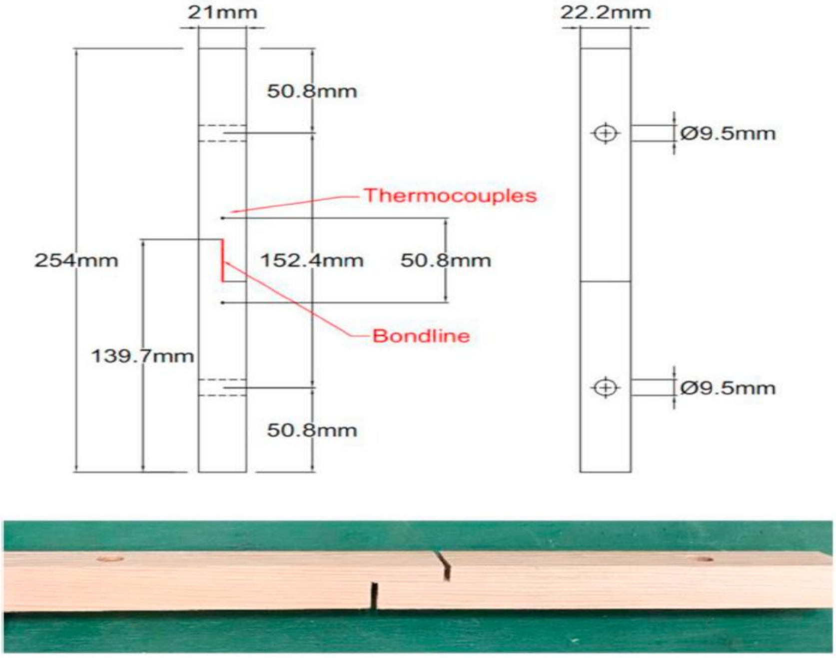

Figure 1. Geometry of the specimen used by Zelinka [7].

Table 1. Properties of wood used in Finite Element Analysis (FEA) [12 – 17].

Parameter	Douglas Fir (DF)	Southern Yellow Pine (SYP)	Spruce Pine Fir (SPF)
E_L *(MPa)*	14,740	13,530	9790
E_T *(MPa)*	737	1055.34	577.61
E_R *(MPa)*	1002.32	1528.89	1253.12
V_{LR}	0.292	0.328	0.422
V_{LT}	0.449	0.292	0.462
V_{RT}	0.390	0.382	0.53
G_{LR} *(MPa)*	943.36	1109.46	1213.96
G_{LT} *(MPa)*	1149.72	1095.93	1174.8
G_{RT} *(MPa)*	103.18	175.89	97.9
Thermal Conductivity, W/(m°C)	1.01	1.12	0.90

Table 2. Coefficient of Thermal Expansion of DF, SYP & SPF [12].

Species	Radial (10^{-6} in/in/°F)	Tangential (10^{-6} in/in/°F)	Parallel (10^{-6} in/in/°F)
Douglas Fir - South	14	19	1.9
Southern Yellow Pine	15	20	2.0
Spruce Pine Fir	13	18	1.8

Table 3. Properties of wood adhesives [18 – 23].

Elastic Properties	Melamine Formaldehyde (MF)	Phenol Resorcinol Formaldehyde (PRF)	Polyurethane (PUR)
Young's Modulus (MPa)	3200	3540	559
Poisson's Ratio	0.33	0.443	0.351
Coefficient of thermal expansion (CTE) (/°F.K)	60×10^{-6}	68×10^{-6}	200×10^{-6}
Thermal Conductivity (W/m.K)	0.5	0.146	0.209

2.2. Thermal Model Analysis

2.2.1. Steady State Thermal Model

For a steady state thermal analysis (using ANSYS 2020 R1) of heat conduction through the specimen. Solid wood is considered as a whole, and the thermal condition is applied on the upper surface (Figure 2). A geometry of two pieces of wood joined with a 25.4 mm glue line is also considered and a thermal condition applied on the upper surface (see Figure 3).

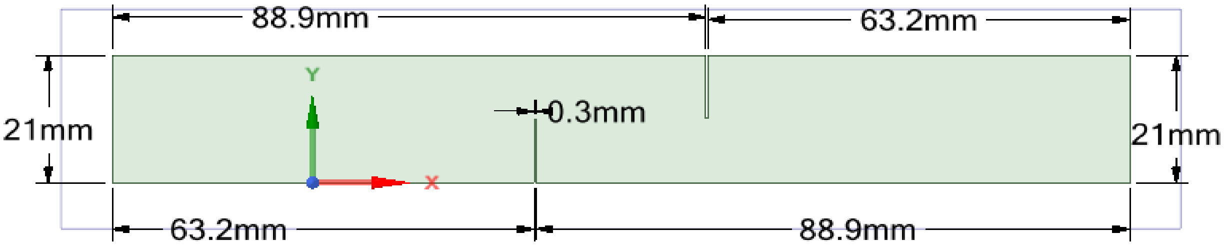

Figure 2. Geometry for solid wood used in thermal analysis.

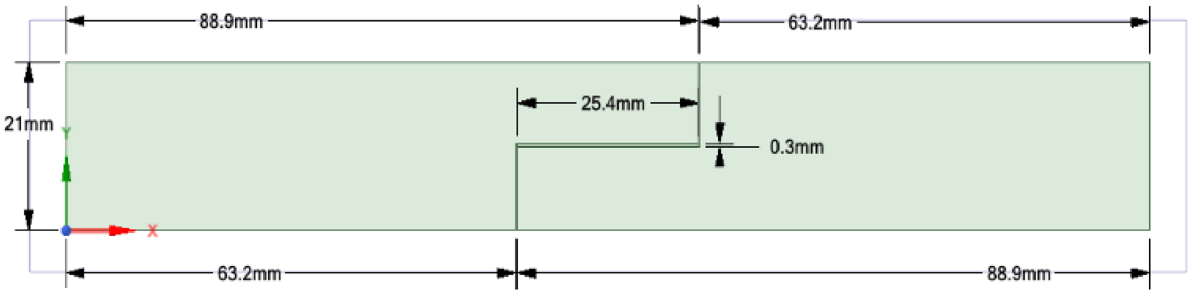

Figure 3. Geometry for wood with a glued lap joint.

To determine the influence of the adhesive layer on heat transfer in CLT; (1) the simulation of heat transfer through solid wood (Douglas Fir), with geometry as in figure 2 above was conducted. A steady state thermal model was developed, heat flow was set to 5.65 W, convective heat transfer coefficient of free air was set to 2.5 x 10^{-6} W/(mm^2.K) [24], temperature solution output was set, the model was then run and results recorded. (2) a steady state thermal model was set up, but this time the thickness of the glue line was taken into consideration, the geometry used was set as in figure 3 and three simulations were run for three different wood adhesives (PRF, MF & PUR) and the results noted.

2.2.2. Analytical model

CLT is produced by gluing timber panels together. According to EN 15425:2017 the thickness of glue layer is 0.3 mm. The dimensions of the specimen used were extracted from the one used in Zelinka et al [7] experiments. The thickness of the specimen was 21 mm, width was 22.2 mm and the length of the glue film was 25.4 mm (see figure 4 below). To show temperature distribution in this specimen, an analytical calculation was performed using Eurocode 5 temperature equation (Eq1) and then heat transfer equation (Eq4). The thermal properties of wood species and glue types used are as in table 1, 2 & 3.

$$T = T_i + \left(T_p - T_i\right)\left(1 - \frac{x}{a}\right)^2 \tag{1}$$

$$T_{out} = T_{in} - \dot{Q}''\frac{dx}{k} \tag{2}$$

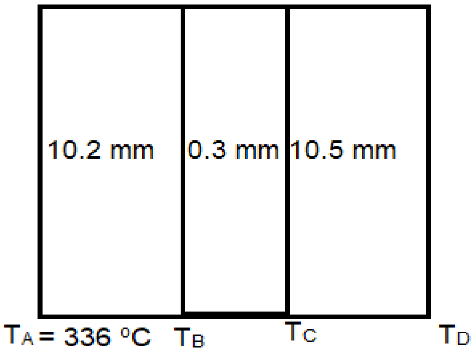

Figure 4. Specimen Dimensions for Analytical Calculations.

In developing the analytical solution, the initial temperature was assumed to be 20 °C (room temperature in the United Kingdom). The heat flux was calculated by dividing the heat energy by surface area (10020 W/m^2). The computations for temperature in and out (T_B and T_C) of the adhesive layer are made by using both Eq1 and Eq4.

2.3. Thermal-Structural Behavior of Wood

Using the geometry in figure 5 below, tensile tests of the three wood species (DF, SP, SPF) were simulated using ANSYS 2020 R1. The surrounding temperature (temperature inside the furnace) was considered as 300 °C. The maximum stress (MPa) and strain (mm/mm) was recorded for temperatures 20 °C, 100 °C, 140 °C, 180 °C, 220 °C, and 260 °C [25]. The geometry used is like the one in Figure 2, because solid wood is used as a control experiment, it has been replicated to avoid confusion that may arise while doing separate analyses in ANSYS workbench.

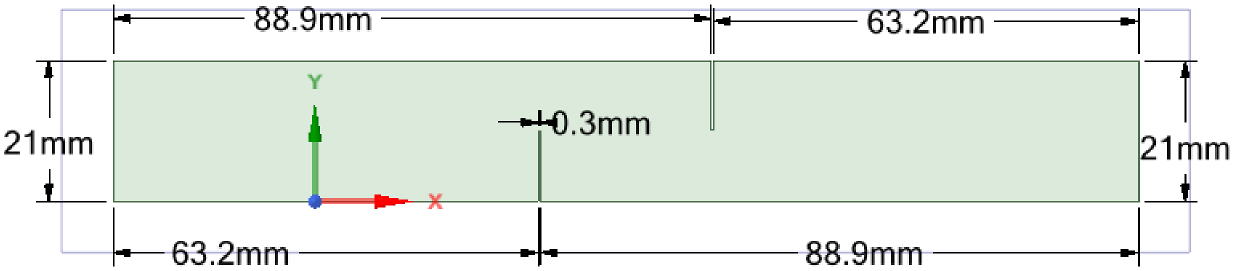

Figure 5. ANSYS set up for tensile test of wood.

2.4. Thermal-Structural Behavior of Adhesive Bond

After developing an understanding of the structural behavior of wood for elevated temperatures below charring temperature of wood, ANSYS geometry was set up to analyze the structural behavior of wood adhesives for temperatures 20 °C, 100 °C, 140 °C, 180 °C, 220 °C and 260 °C as in figure 6 below. The values of maximum stress (MPa) and strain were recorded for respective temperatures. Three wood adhesives were simulated (MF, PRF and PUR) and the results compared to determine which one performs better at high temperatures. Douglas Fir was used as a control experiment, and its stresses and strains plotted together with those of the adhesives [25].

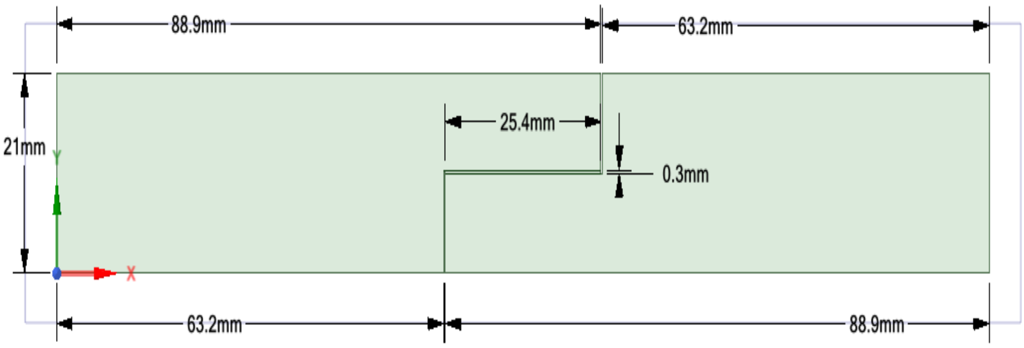

Figure 6. ANSYS set up for tensile test of Adhesive.

The results from analytical calculations and ANSYS simulations are presented in the next section (results and analysis). The graphs were plotted in excel sheets and then transferred to Microsoft word document for further processing.

3. Results and Analysis

3.1. Steady State Thermal Model

Douglas fir (DF) was used as the main timber species in these simulations and the results from heat transfer simulation in solid wood and bonded wood with different adhesives (PRF, MF, PUR), are as follows (Figure 7, 8, 9 & 10);

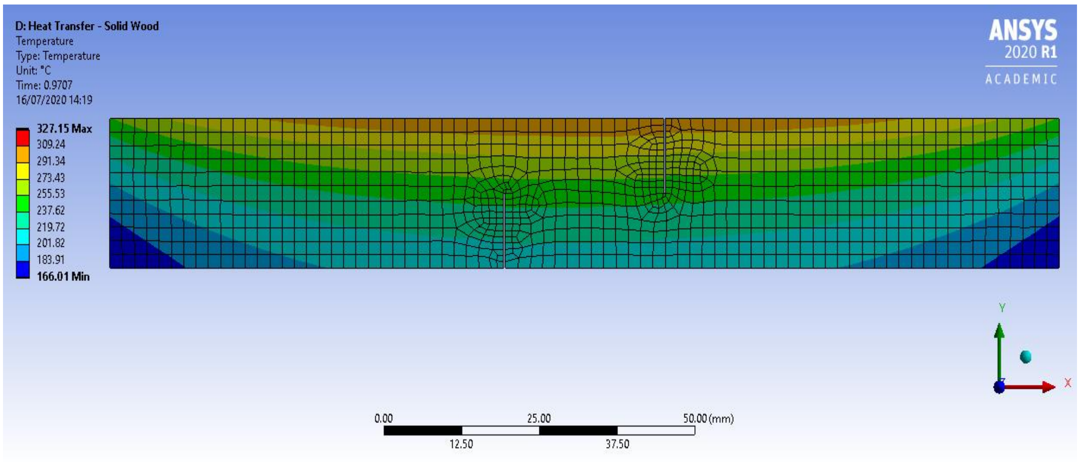

Figure 7. Temperature distribution in solid wood (DF).

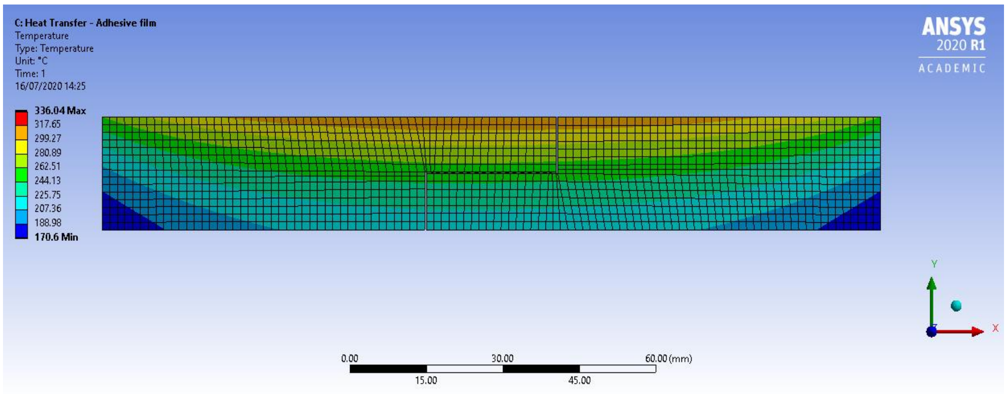

Figure 8. Temperature distribution in a composite of DF and PRF.

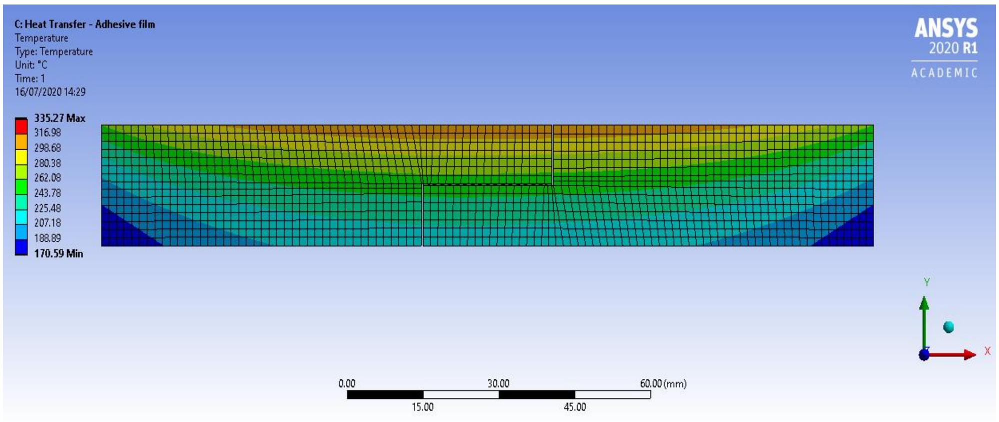

Figure 9. Temperature distribution in a composite of DF and MF.

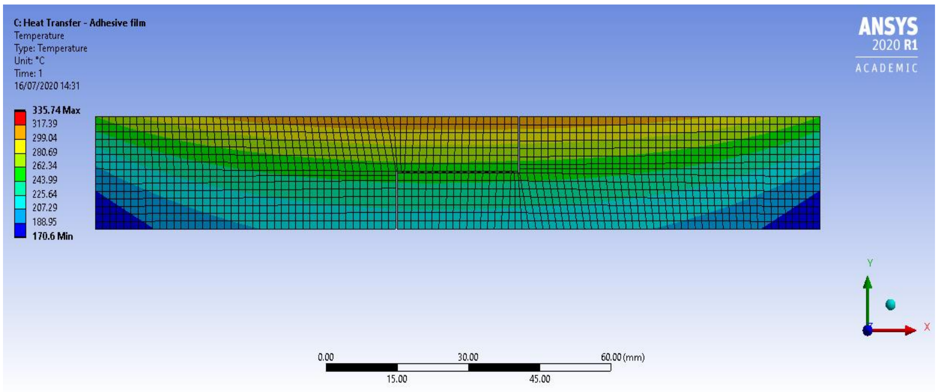

Figure 10. Temperature distribution in a composite of DF and PUR.

From steady state thermal simulations, the adhesive layer lies in the region between 10.2 to 10.5 mm, which is within the green region. For solid wood specimen, the green region lies between temperatures of about 238 to 256 °C, for wood bonded with PRF, the green region lies between temperatures of 244 to 263 °C, for wood bonded with MF, the green region lies between temperatures of 244 to 262 °C and finally for solid wood bonded with PUR the green region lies between temperatures of 244 to 262 °C. See table 4 for summary of results for temperature drop in the green zone for respective specimens.

Table 4. Summary of Steady State Thermal Simulation Results.

Specimen	Temperature Drop (°C)
Solid Wood - Douglas Fir (DF)	18
DF bonded with Phenol Resorcinol Formaldehyde (PRF)	19
DF bonded with Melamine Formaldehyde (MF)	18
DF bonded with Polyurethane (PUR)	18

3.2. Analytical Model

The analytical model was intended to determine the temperatures into the adhesive layer and out of the adhesive layer, that is temperature T_B and T_C respectively. The calculations were based on the geometry shown in figure 6. These calculations include Eurocode 5 formula and thermal conductivity formula as presented in table 5 below.

Table 5. Summary of Analytical Results.

Material	Heat Flux (W/m2)	Thermal Conductivity (Wm^{-1}K^{-1})	T_B (°C)	T_C (°C)	Temperature Drop (°C)
		Eurocode 5 Equation (Eq1)			
CLT - DF			175	172	3
		Thermal Conductivity Equation (Eq4)			
Solid Wood - DF	10020	1.01	235	232	3
Adhesive layer - PRF	10020	0.146	235	214	21
Adhesive layer - MF	10020	0.5	235	229	6
Adhesive layer - PUR	10020	0.209	235	220	15

The results from the analytic model show that the Eurocode 5 temperature equation (Eq1) returns very low temperatures ($T_B = 175$ °C and $T_C = 172$ °C) as compared to Eq4 and this gives proof that char layer has very good insulating properties. While for adhesive layers the temperatures in is the same as for solid wood and temperatures out show significant reduction, which depends on the thermal conductivity of the adhesive. If solid wood is used instead of adhesive, $T_C = 232$ °C, when substituted by adhesive, T_C = 214 °C (PRF), 229 °C (MF), and 220 °C (PUR). From that we can deduce that there is a significant drop in temperature out, due to the adhesive layer as compared to solid wood. Therefore, during manufacture of CLT we need to consider the adhesive layer's thermal properties.

3.3. Thermal – Structural behavior of wood

When wood is exposed to heat, the structural performance of wood reduces with increase in temperature. Therefore, these effects were simulated using Douglas Fir (DF), Southern Yellow Pine (SYP) and Spruce Pine Fir (SPF) wood species. The purpose of this simulation was to act as a control experiment, the results of which will be compared with those from the adhesives' tests. The results from the simulations are presented below in table 6, 7 & 8. The graphs of stress against temperature and strain against temperature for the three wood species are also presented in the figures 11 & 12.

Table 6. Douglas Fir (DF).

Temperature (°C)	Stress (MPa)	Strain (mm/mm)
20	102	0.0278
100	83.7	0.0198
140	74.4	0.0159
180	65.1	0.0120
220	55.8	0.00805
260	46.5	0.00724

Table 6. shows the stress and strain of Douglas Fir, simulated for specified temperatures above. The results show decreasing values of stress and strain with increasing values of temperature.

Table 7. Southern Yellow Pine (SYP).

Temperature (°C)	Stress (MPa)	Strain (mm/mm)
20	115	0.0298
100	93.5	0.0213
140	82.5	0.0171
180	71.6	0.0128
220	60.5	0.00866
260	49.5	0.00703

Table 7 shows the stress and strain of Southern Yellow Pine, as simulated for temperatures indicated above. Just like for DF, the results show decreasing values of stress and strain with increasing values of temperature.

Table 8. Spruce Pine Fir (SPF).

Temperature (°C)	Stress (MPa)	Strain (mm/mm)
20	82.7	0.0349
100	66.7	0.0252
140	58.7	0.0204
180	50.6	0.0155
220	42.6	0.0107
260	34.5	0.00764

Table 8. shows decreasing stress and strain values of Spruce Pine Fir with increasing temperature as simulated using ANSYS Steady State analysis system. From tables 6, 7 & 8, SYP has the highest strength, while SPF has the lowest strength. The reverse is true for strain values at all temperatures.

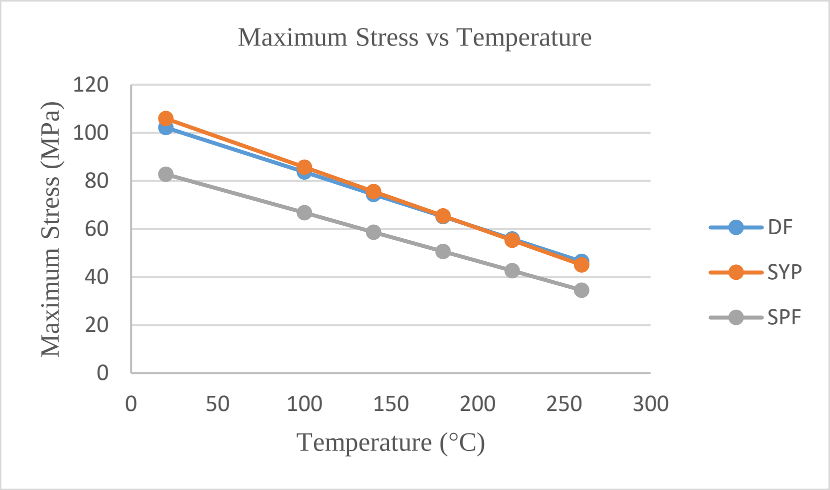

Figure 11. Graph of stress against temperature for the three tree species.

From the graph in figure 11 above, we can see that maximum stress of the tree species simulated reduces with increase in temperature. Southern Yellow Pine has a higher maximum stress, followed by Douglas Fir and then Spruce Pine Fir. From this graph we can also conclude that different tree species have different thermal – structural properties and these can be considered when designing CLT for load bearing elements.

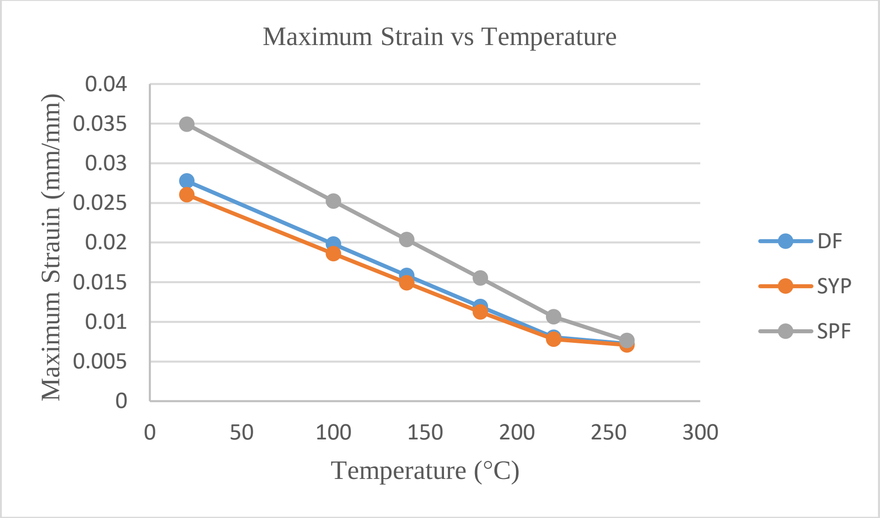

Figure 12. Graph of Strain against Temperature for the three tree species.

A plot of maximum strain against temperature (figure 12 above), shows that the maximum strain reduces with increase in temperature. These values are different for each tree species simulated. With Spruce Pine Fir having a higher strain, followed by Douglas Fir and then by Southern Yellow Pine.

3.4. Thermal - Structural Behavior of Adhesives

Three adhesives comprising PRF, MF and PUR were simulated using ANSYS mechanical 2020 R1 at different temperatures and the results are presented below. At room temperature (20 °C), the adhesive joint is designed to be stronger than solid wood at the same temperature. The simulation results for stress (MPa) and strain (mm/mm) for all the three adhesives is presented in Tables 9, 10 & 11 respectively.

Table 9. PRF Adhesive.

Temperature (°C)	Stress (MPa)	Strain (mm/mm)
20	131.95	0.069581
100	106.83	0.052427
140	94.215	0.043894
180	81.562	0.035399
220	68.872	0.026958
260	56.145	0.018615

Table 10. MF Adhesive.

Temperature (°C)	Stress (MPa)	Strain (mm/mm)
20	128.37	0.052469
100	104.28	0.039939
140	92.2	0.033707
180	80.095	0.027506
220	67.967	0.021352
260	55.815	0.015286

Table 11. PUR Adhesive.

Temperature (°C)	Stress (MPa)	Strain (mm/mm)
20	115.67	0.15237
100	94.253	0.11392
140	83.515	0.094933
180	72.756	0.076201
220	61.976	0.057928
260	51.175	0.04066

The plot of stress against temperature for the three adhesives is shown in figure 13. From the results we can conclude that the maximum stress of the adhesives reduces with increase in temperature from 20 °C to 260 °C. We are also able to prove from these results that the maximum shear stress of the three adhesives is greater than the maximum shear stress of the solid wood species (Douglas Fir) studied at room temperature.

From the graph in figure 13, The researcher was also able to notice that Phenol Resorcinol Formaldehyde has the highest shear strength at room temperature, followed by Melamine Formaldehyde resin, and then Polyurethane resin.

These simulation results have helped us understand the performance of wood adhesives used in the production of CLT. We can tell that MF and PRF have better thermal – structural properties as compared to PUR and therefore, they can be recommended for production of CLT panels used in load bearing timber structures.

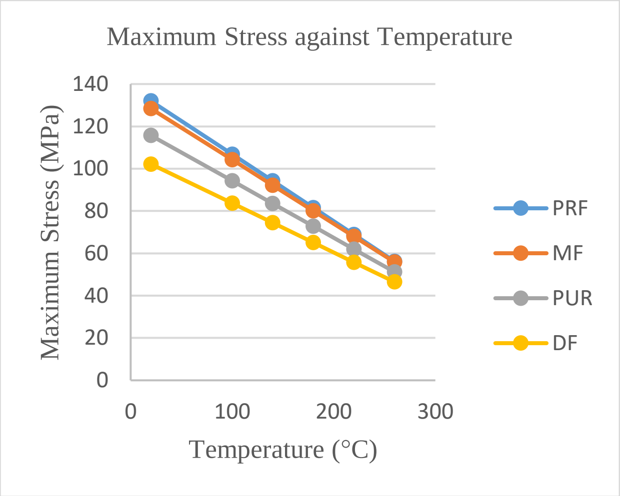

Figure 13. Graph of Stress against Temperature for the three wood adhesives.

When strain is plotted against temperature for the three adhesives, we can see from the graph in figure 14 that PUR has the highest strain, followed by PRF, then MF. This implies that there are higher chances of delamination occurring caused by displacement in the glue line for PUR, than for PRF and MF. The graph also indicates that the strain for all the three adhesives reduced with increase in temperature from 20 °C to 260 °C. The results from the graph also show that the strain of Douglas Fir wood is almost the same as Melamine Formaldehyde. This indicates that Melamine Formaldehyde is rigid like solid wood since there is a very slight increase in length at 260 °C. With Melamine Formaldehyde and Phenol Resorcinol Formaldehyde as structural adhesives, the load bearing structures will have the ability to retain structural integrity even at high temperatures, hence giving the building occupants enough time to evacuate timber building in time before it collapses.

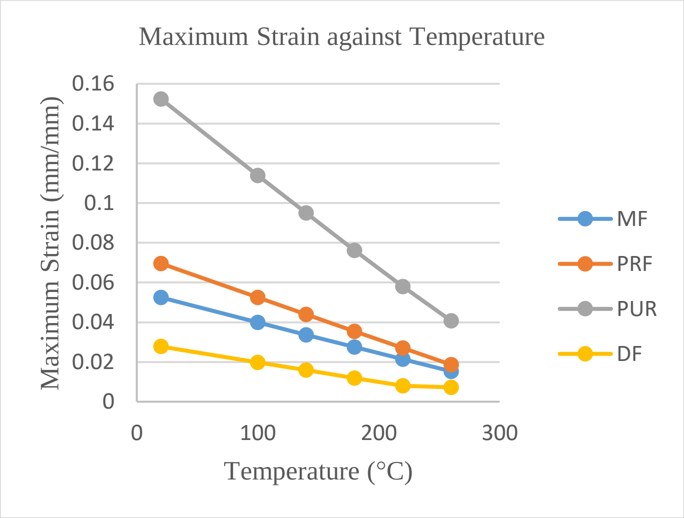

Figure 14. Graph of Strain against Temperature for the three wood adhesives.

4. Discussions, Conclusions and Future Research

4.1. Discussions

The discussion of the results has been performed to give a clear insight on how the objectives of the research have been met. This includes a brief account on how the results agree or disagree with the previous research (see summary in tables 12 & 13). The research objectives have been met as explained below, for objective;

Table 12. Comparison of Wood Behavior in Experimental [7] and Simulation Results.

	Experimental Results [7]	**Simulation Results**
Stress	• DF had a higher stress, followed by SYP and then SPF. Though SPF had a higher stress at room temperature than SYP. • Stress reduced with increase in temperature.	• SYP had a higher stress than DF and SPF. These results are supported by the values in Wood handbook [13]. • Stress reduced with increase in temperature.
Strain	• SYP had a higher strain, followed by SPF and then DF. • Strain reduced with increase in temperature.	• SPF had a higher strain, followed by DF and then SYP. • Strain decreased with increase in temperature.

Table 13. Comparison of Adhesive Behavior in Experimental [7] and Simulation Results.

	Experimental Results [7]	**Simulation Results**
Stress	• For the solid wood and all adhesive systems, the shear strength decreased as the temperature increased. • PRF had a similar strength as DF at all temperatures.	• For solid and all adhesive systems, stress decreased with temperature increase. • PRF had a higher stress, followed by MF, PUR and then DF

i. To determine the influence of the adhesive layer on thermal behavior of CLT

From steady state thermal analysis of temperature variation along the green zone, there was a drop of 18 °C for solid wood (DF), 19 °C for DF bonded with PRF resin, 18 °C for DF bonded with MF resin and 18 °C for DF bonded with PUR resin. Also, from analytical solution the drop in temperature as computed from Eurocode 5 equation (Eq1) for CLT, was the same as that of solid wood computed with thermal conductivity equation (Eq4), which was 3 °C for 0.3 mm thickness of the specimens. These results clearly show that the thickness of the wood glue has very little or no influence on the thermal behavior of CLT, implying that the thermal properties of CLT are the same as for solid wood. These results agree with what is published in the Swedish Wood CLT handbook [26]. However, from the analytical solution, the drop in temperature for DF is 3 °C, for DF bonded with PRF resin (across the bond line) the drop in temperature is 21 °C, for DF bonded with MF resin the temperature drop is 6 °C and finally for DF bonded with PUR resin is 15 °C. Therefore, according to these results, the adhesive layer has a strong influence on the thermal properties of CLT and these effects vary with the type of adhesive. The results from steady state simulation and show similar thermal behavior between solid wood and bonded wood and yet results from analytical solution (Eq4) show significant influence of adhesive layer on thermal behavior of bonded wood, with all temperature drops greater for bonded wood than for solid wood. These results are supported by Klippel [27], who discussed that highly crosslinked adhesives have good thermal stability than low crosslinked adhesives. PRF and MF are highly crosslinked and PUR is low crosslinked, implying that PRF and MF perform better at high temperatures above 220 °C as compared to PUR adhesive [28]. Even though there is a measurable drop in temperature across the glue line, this does not necessarily pose a grave danger.

i. To model the thermal behavior of solid wood

The maximum stresses and strains of the three species of solid wood (DF, SYP, SPF) simulated exhibit a linear decrease with increase in temperature, this is in line with results from Zelinka et al [7]. According to Zelinka et al [7], Southern Yellow Pine data exhibited the lowest strength and modulus as compared to Douglas Fir and yet based on the Wood Handbook, the Southern Yellow Pine should be the strongest of the species tested and have a stiffness comparable to that of Douglas

Fir [13]. In our simulation results, Southern Yellow Pine has the highest maximum shear stress (slightly above Douglas Fir) and this agrees with what is published in the Wood Handbook [13].

i. To determine the mechanical properties of wood adhesives, especially loss in the adhesive bond strength due to rise in temperature.

From simulation results, at room temperature the maximum stress for all the three wood adhesives (PRF, MF, PUR) is greater than the maximum stress of Douglas Fir at the same temperature. By design adhesives are supposed to be stronger than solid wood at room temperature [29].

The maximum stress of the adhesives also reduced with increase in temperature, PRF has the highest maximum stress at all temperatures simulated, followed by MF and then PUR. All these three adhesives have higher stresses at all temperatures than solid wood (Douglas Fir). There was a reduction in maximum stresses of adhesives with increasing temperature until 260 ^{o}C, this agrees with findings from other authors [7, 27].

The graphs of strain against temperature, show that PUR has the highest strain and that it is more ductile than MF, PRF and wood. PUR is therefore considered as an adhesive with the highest flexibility of relevant wood adhesives and may not be used for structural purposes. Current research also provides evidence that thermal softening depends on the formulation of PUR [30, 31].

4.2. Conclusions

The following conclusions were derived from this study.

- The adhesive layer has little influence on the thermal properties of CLT and therefore, the thermal properties of glued timber are the same as for solid timber. Wood adhesives have a significant influence on the structural properties of CLT.
- The stresses and strains of wood species decrease with increase in temperature.
- The stresses and strains of wood adhesives reduce with increase in temperature.
- PRF and MF are better structural adhesives than PUR.
- With accurate material properties, the thermal -structural behavior of wooden structures can be analyzed using ANSYS without having to carryout small scale or large-scale experiments.
- Finally, the results from this research to a bigger extent support the experimental findings by Zelinka et al [7].

4.3. Future Research

From this research, information on thermal and mechanical properties of wood could easily be retrieved from online sources. While, on the other hand there is limited information on thermal and structural properties of wood adhesives. Therefore, more studies should be conducted on thermal – mechanical properties of wood adhesives. Also, the thermal and mechanical properties of timber species and wood adhesives manufactured in the UK must be experimented and archived, to ease numerical analysis. There needs to be a study of assemblies rather than rectangular slabs and for higher temperatures and perhaps defects such as ducting also need more study. Also, the data used in this simulation is not the exact data derived from the specimens used by Zelinka et al [7], therefore, it is recommended that for more accurate results, data from the same experimented specimens should be used in the simulation analysis.

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