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THE SURFACE TEMPERATURE OF OUTDOOR UNDERCOVER GLUED LAMINATED TIMBER

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ABSTRACT: The surface of glued laminated timber used in outdoor undercover conditions can deteriorate when exposed to the energy of heated air masses and to direct solar radiation. Knowledge of the in-service surface temperature of exposed glued laminated timber can help predict deterioration and improve structure performance. The energy equalization of radiation heating and convection cooling can be applied to examine and model surface temperature, including the temperature of different surface finishes. Four surface finishes were studied; a black spirit based stain, an oil based liming white, a clear epoxy resin and no finish. A total of 44 glued laminated timber surfaces where exposed in sub-tropical Australia and evaluated at three different times, including a summer and a winter solstice. A total of 16 surfaces where orientated horizontally facing upwards with 4 facing downwards, while two sets of 12 beams where oriented vertically, with one set facing northwards and one set facing southwards. A model using publically available weather station data (air temperature, wind speed, solar radiation) was used to estimate solar absorptance and to predict the temperature of exposed glued laminated timber in outdoor undercover conditions.

KEYWORDS: glued laminated timber, surface temperature, solar radiation, absorptance

1 – INTRODUCTION

The surface integrity of glued laminated timber, can influence the durability, structural, aesthetic and fire performance of a structure. One deterioration agent which may adversely impact upon in-service glued laminated timber surfaces, is the kinetic energy associated with the motion of molecules within in the material. Energy in a material can be measured through the average kinetic energy, which is directly proportional to temperature. Materials are subject to changing kinetic energy (temperature), either increasing energy (heating) or decreasing energy (cooling), which may cause deterioration and affect performance. The temperature of glued laminated timber may, (i) influence biological deterioration by creating optimal conditions for organism growth and wood consumption [1] (ii) contribute to stability issues, like dimensional variation, driven by moisture content changes, which are influenced by temperature [2], (iii) cause a lowering of structural characteristics via delignification of the wood [3], (iv) induce changes in surface morphology including delamination and cracks, with potential to increase combustion rates [4] and may also (v) impact product appearance by facilitating chemical reactions which can fade or darken surfaces. [5]. An example of temperature induced deterioration, would be solar radiation acting on wooden window frames, where high temperature may cause joint cracking allowing rain water penetration of joints, [6] resulting in deterioration. Thermal energy changes in the surface of glued laminated timber may not only adversely affect the wood but also the adhesive, the wood/adhesive bond, as well as any associated surface connection systems. Reliably predicting the in-service temperature of glued laminated timber surfaces can help design strategies to improve durability, structural, aesthetic and fire performance.

The mechanisms for thermal energy transfer to and from glued laminated timber surfaces are i) conduction, where adjoining solid materials gain or lose thermal energy via direct contact, as may occur with a metal plated connection system, ii) convection, where the movement of a liquid or gas at a surface may transfer thermal energy to or from a surface, and iii) radiation, where thermal energy from a non-contact heat source or the timber itself may be lost or gained. Outdoor undercover glued laminated timber surfaces in structures are most commonly exposed to increases in thermal energy via energised atmospheric gases flowing across a surface, and also via exposure to energy from solar radiation. This investigation examines glued laminated timber surfaces in outdoor undercover climatic conditions, exposed to changing air temperature and solar radiation. The impact of precipitation on surfaces is specifically excluded from this study as shielding of glued laminated timber surfaces from direct wetting is considered good building practice.

The gases in earth's atmosphere are heated by radiation. The rotation of the earth results in mixing of atmospheric gases and movement of atmospheric heat around the planet, resulting in dynamic air masses with different temperatures. Glued laminated timber surfaces are exposed to the thermal energy of these heated atmospheric currents, which vary over time due to climatic events and cycles. As a result, energy may be

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transferred between the atmosphere and a glued laminated timber surface, resulting in surface temperature changes. When solar radiation is not present, then surface temperatures reflect the same energy conditions of the air to which it is exposed. i.e. thermal equalization of a wood surface and an air mass, via convection. This may result in temperature increases or decreases depending on the air-surface temperature difference. Natural or forced air convection systems are common processes used to season wood to a stable moisture content, suitable for end use.

The Bureau of Meteorology in Australia [7] provides a range of services including obtaining and maintaining climatic information. The Bureau of Meteorology measures air temperature automatically at weather stations throughout Australia. Temperature readings are commonly recorded at half hourly and daily intervals. Air temperatures in Australia are reported at 9 am and 3 pm each day. Air temperature data is also aggregated and analysed to give daily, monthly, yearly climatic statistics. The data is freely and publically available.

Fusion processes in the sun result in radiant heat being emitted in all directions. Earth's surface intercepts solar radiation emissions and due to its orbit, rotation, shape and tilted axis, the distribution of the sun's thermal energy on the earth's surface varies. Solar radiation is determined for most weather stations in Australia. The Bureau of Meteorology uses a computer model to estimate the total amount of solar radiation that reaches a horizontal surface on the earth in a day, called the "daily global solar exposure". An energy budget calculation is made at each surface evaluation location, using hourly visible radiation information i.e. radiances from operational geostationary satellites. Hourly irradiances are then integrated over night to give daily insolation totals in megajoules per square metre, i.e. the "daily global solar exposure". Solar radiation on horizontal surfaces is the default value reported, with calculations required to determine radiation values for non-horizontal surfaces and for surfaces facing a particular compass direction. This involves the consideration of latitude and any local obstructions which may impact on the solar energy received by a surface.

The moisture content of wood for a constant air temperature and constant relative humidity is well known.[2] Wood is a hygroscopic material exhibiting physical changes in direct response to changing moisture content. Solar radiation is not normally considered in moisture content modelling as most timber in structures is used internally or shielded in some way to prevent direct exposure to solar radiation.

Heat transfer physics have been applied to glued laminated timber surfaces in this study. Consider a closed thermodynamic system with a horizontally orientated glued laminated timber surface exposed to outdoor undercover conditions via atmospheric and sun exposure, excluding precipitation. Two mechanisms for heat transfer exchange between the surface and the exposure conditions are considered. i.e. convection and radiation Refer Figure 1.

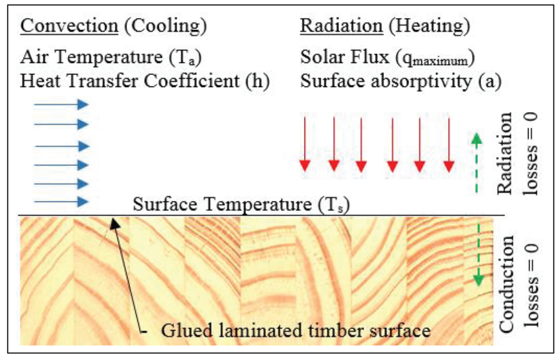

Figure 1. Closed thermodynamic system of glued laminated timber surface exposed to outdoor undercover conditions.

Assuming a steady state closed thermodynamic system, energy can be exchanged between the surface and the conditions above and below the surface, while maintaining energy equilibrium. The heat energy (q) may be transferred to a unit surface area in a unit of time. Heat can be considered to be transferred to the surface from solar radiation and lost or gained from the surface through convective cooling. It is assumed in this study that the surface loses no heat via radiation, and also loses no heat into the glued laminated timber via conduction. These assumptions are justified by the relatively small timescales involved, the low temperatures involved in this system and that wood has a relatively low thermal conductivity, compared to other common materials making it a natural insulator. [8] The nett energy of a steady state thermodynamic system will be 0, i.e. the rate at which heat from solar radiation (q(radiation)) is transferred to the glued laminated surface is assumed to be equal to the rate at which heat is lost from the surface (q(convection)), due to the flow of air above the surface via convection. i.e. q(radiation) - q(convection) = 0 , or alternatively

$$q(\text{radiation}) = q(\text{convection}) \quad (1)$$

The heat transferred to the surface will depend on the surface characteristics of the glued laminated timber. Ideal black bodies, are known to transfer 100% of the available solar radiation. Real glued laminated timber however, will not absorb all solar radiation just a proportion of it. This proportion represents the unique radiation absorption characteristics of the surface and is known as the solar absorptance factor (a) with values between 0 and 1. This absorptance factor may relate to the colour, texture and/or material at the surface, and the determination of its value is an objective of this study. Where the full amount of solar radiation available to heat a surface is (q(maximum)), then,

$$q(\text{radiation}) = a \cdot q(\text{maximum}) \quad (2)$$

The convection heat transfer rate associated with cooling the surface is given by Newton's Law of Cooling, where the convection heat transfer coefficient (h) has units of watts/m^2.degrees Celcius and the temperatures of the surface (T_s) and the air (T_a) are in degrees Celsius. The convection heat transfer coefficient depends on the flow of the fluid carrying the thermal energy over the surface. The heat transfer coefficient and the absorptance factor are both assumed to be uniform over the surface. Thus the convection heat transfer rate is given by,

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$$q(convection) = h.(T_s - T_a) \quad (3)$$

Combining equations 1, 2 and 3 to determine the surface temperature (T_s) of the glued laminated timber, gives,

$$T_s = T_a + (a \,.\, q(maximum)) / h \quad (4)$$

The objective of this study is to measure the surface temperature of glued laminated timber exposed to outdoor undercover conditions, and to compare these measurements to a predicted surface temperature, using the simplified thermodynamic approach described herein. The impact on surface temperature of various finishes (black, white, epoxy, unfinished) applied to glued laminated timber surfaces is also studied. The increasing relevance of solar absorptance as a material characteristic is also of interest, given its referencing in national building provisions relating to energy efficiency. [9] This study provides solar absorptance values for glued laminated timber surfaces.

2 – MATERIALS AND METHODS

Two field trials were used in this study, a discrete day only field trial, applied on three different dates on 4 radiata beams with 8 surfaces, and an 18 month continuous trial, primarily established to study surface deterioration in 36 glued laminated hybrid pine beams. The trial site and exposure conditions was the same for both beam types.

The set of 4 radiata beams were all manufactured from seasoned plantation grown radiata pine laminates, which were 20 mm thick, 120 mm wide and 140 mm long. All radiata beams were manufactured, with 7 laminations per beam and 6 gluelines per beam, resulting in a finished beam that was 140 mm thick, 120 mm wide and 140 mm long. All four beams were matched for wood quality to ensure any performance differences were not due wood variation. The average density of radiata beams was 415 kg/m^3, while the average moisture content was 10%. A commercially available one component polyurethane adhesive, 'Loctite HB S309 Purbond', manufactured by 'Henkel' was used to manufacture both the radiata and the hybrid pine beams. The four radiata beams where exposed with one finished horizontal surface facing upwards and one finished surface facing downwards.

The set of 36 hybrid pine beams were all manufactured from a hybrid pinus species developed and grown in plantations in Queensland, Australia. This wood resource is a locally-developed hybrid of slash pine (Pinus elliottii var. elliottii) and Caribbean pine (Pinus caribaea var. hondurensis). It is used commercially in Queensland, Australia to manufacture timber products, including glued laminated timber. The timber used in this trial was sourced from an earlier resource characterization study. [10]. This timber had been stored in dry open under cover conditions for several years in Brisbane (250 kilometres south of the trial site), with good acclimatization to ambient environmental conditions. Considerable research information had been previously gathered on this timber. Sawn sections of approximately 100 x 38 mm were selected to have a stratified and wide distribution of the surface characteristics being studied. Pieces of 1.8 m in length were selected and sorted into groups based on the approximate growth ring surface orientation on the exposed surface. Growth ring surface orientations less than 45 degrees were used to make one glued laminated beam, while those greater than 45 degrees were used to make a second beam. Individually these beams were referred to as the tangential faced beam and the radial faced beam. This reflected typical manufacturing practices where laminates often have similar orientations. It also allowed deterioration differences between the two orientation groups to be evaluated. Wood surfaces were also selected to ensure a range of surface distances from the tree pith, (20 mm to 140 mm). All laminates were machined to a dressed thickness of 32 mm prior to beam manufacture. Following manufacture, the average density and average moisture content of tangential faced beams were measured as 545 kg/m^3 and 9.9%, while the radial faced beams were measured as 510 kg/m^3 and 10.0%, respectively.

All hybrid beams were sealed to restrict moisture movement on all but the surface intended for exposure. The sealing of beam ends, sides and backs was undertaken with a two part epoxy resin applied directly to the wood surface, followed by a 0.63 mm aluminium foil applied directly to the tacky resin prior to its hardening. This effectively stuck the aluminium foil to the unexposed beam surfaces, providing a barrier to moisture transfer. This was undertaken to minimize the impact of moisture changes from the five sealed faces, on the exposed surface being studied for deterioration.

A total of 20 surfaces (18 hybrid beams and 1 radiata beam) were left unfinished, while the remaining three sets of 8 surfaces (6 hybrid beams and 1 radiata beam) had the following commercial finishes applied. i) Black – 'Feast Watson', Black 'Prooftint', Spirit based stain, applied with a soft cloth to achieve an even colour consistency with a surface coverage of about 45 millilitres per square metre, ii) White – 'Feast Watson', Liming White, Oil based stain, applied with a soft brush to achieve an even colour consistency with a surface coverage of about 65 millilitres per square metre, iii) Epoxy, 'Protite' Fiberglass Resin - Clear, low styrene emission epoxy resin, 2 part mix with 'Protite' resin catalyst hardener, applied with a soft brush to achieve an even surface coverage of about 220 grams per square metre. Figure 2 shows the radiata pine beam surfaces following application of each finish product.

The 18 month continuous trial to examine glued laminated timber surface deterioration was established on the 1st January 2021 in coastal Queensland Australia. This trial exposed 36 beams to 3 solar exposure conditions; horizontal, vertical north facing, vertical south facing; representing typical exposure orientations in buildings. At three different times through this trial period, surface temperature measurements for each beam were taken at regular intervals during daytime exposure, using a hand-held calibrated infrared based temperature measuring device. Measurements were taken, on the 23/8/2021 (a preliminary study to confirm test methodology), the 21/12/2021 (the summer solstice) and on the 23/6/2022 (2 days past the winter solstice).

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Figure 2. Radiata pine beam surfaces following the application of finish products.

Solar radiation calculation for sub periods of each day, corresponding to the measurement times, was facilitated by the entire measurement period being free of cloud cover. The 21/6/2022 was the desired winter solstice date, however it was not used as an analysis of measurements showed some cloud cover at about midday, blocking some solar radiation and adversely affecting hourly solar radiation calculation. Two days later on the 23/6/2022 clear skies allowed this alternative date to be used. Radiata pine beams where exposed for the duration of the whole day on each date only, after which they were returned to internal dark storage conditions. Table 1 summarizes the two field trials used in this study and the number of exposed surfaces and their orientation.

Horizontal surface orientation is the standard plane used for determining the magnitude of solar radiation reaching the earth's surface.[11] Where a surface is not horizontal and faces towards a particular compass direction, then solar radiation exposure will be differ, and can be calculated. For instance, the latitude of the field trial site in this study results in a solar radiation daily dose on a vertical north face, which is usually less than the maximum horizontal dose, except near the winter solstice where it is slightly greater due to the suns declination at this point in the solar cycle. A south facing vertical surface was selected in this study as it represents a negligible solar radiation dosage and reflects the solar radiation which may typically impact a surface from indirect solar radiation. Product width was also investigated as a parameter in the deterioration study with three surface widths included for all unfinished beams, for each of the three different solar exposure conditions. i.e. 5 laminations (160 mm), 10 laminations (320 mm) and 15 laminations (480 mm).

Both sets of beams were exposed to a sub-tropical environment located in Queensland Australia, at a latitude of -25.3061 degrees and a longitude of 152.8710 degrees. The exposure site is 20 metres above sea level and is located 2 km from an Australian Government Bureau of Meteorology Weather Station (ID 040405, Latitude -25.3220 degrees, Longitude 152.8817 degrees, height 13 m metres). The climate in this region is classified as humid sub-tropical and is characterized by hot and humid summers and cool to mild winters. [12] Approximately 20% of the world's population live within this type of temperate zone with no dry season. [13] This represents major climatic regions on all continents expect Antarctica.

All beams were supported at least 400 mm above the ground with open ventilation to all exposed surfaces. Protection from direct precipitation was achieved through the use of a 0.8 mm clear polycarbonate profiled sheet, positioned about 200 mm above the horizontal beams and overhanging both the horizontal and vertical beams by a distance which formed an angle of approximately 40 degrees from the sheet edge to the extremity of the beams. Relative humidity and air temperature were both measured and logged at 10 minute intervals at the trial site using a commercial device. The hybrid beam exposure trial commenced on the 1st January 2021 and ceased on the 1st July 2022, after 18 months.

Table 1. Summary trial details and surface numbers for each trial

Field trial details		**18 month field trial** of 36 plantation grown hybrid pinus species beams			**Three - 1 day trials** of 4 plantation grown radiata pine beams	
Purpose		Deterioration Study			Temperature Study	
Beam size		320 x 290 x 80			140 x 140 x 120	
Laminate number and thickness		10 laminations of 32 mm, except in unfinished beams where 15 and 5 laminations of 32 mm were also made.			7 laminations of 20 mm	
Solar radiation exposure		Horizontal up	Vertical north facing	Vertical south facing	Horizontal up	Horizontal down
Surface finish & Beam surface no.	None	6	6	6	1	1
	Black	2	2	2	1	1
	White	2	2	2	1	1
	Epoxy	2	2	2	1	1

3 – RESULTS

3.1 Solar Radiation Exposure

The three combinations of surface orientations and directional exposures adopted in this field trial, represent solar radiation exposure typical of which may be encountered in timber structures in the southern hemisphere. i.e. from the most severe (horizontal) with full sun exposure, to partial sun exposure (north facing and vertical) and to negligible sun exposure (southern facing and vertical). All beams were static during the exposure period and were not moved in any way. Solar radiation varies throughout the day as a result of the suns position in the sky and the magnitude of any radiation obstruction, such as clouds, vegetation or other structures. Vegetation obscured some radiation in this trial, particularly in the early morning and in the late afternoon when the sun was low in the sky. The obstruction impact was considered negligible and not accounted for in the subsequent analysis. Daily solar radiation doses over the full trial period are shown in figure 3 for each beam orientation and facing direction. The dips in all curves reflect reduced solar radiation due to cloud cover.

The daily radiation dose can be theoretically apportioned throughout each of the three trial days based on knowledge of the sunrise and sunset times assuming a symmetrical sinusoidal radiation distribution, with a peak radiation at the culmination time. Figure 4 shows the assumed distribution of solar radiation throughout the trail days for the horizontal and north facing surfaces. This distribution was used to determine an hourly solar radiation dose for the purpose of calculating absorptance and then modelling surface temperature.

Table 2 summarizes the solar and measurement details for each trial date. Temperature was measured at about 1.25 hourly intervals for each of the 44 surfaces.

3.2 Radiata Pine – Actual Temperature

The four radiata pine beams had two surfaces exposed for the three individual days evaluated, with one surface on each beam being orientated horizontally upwards and the opposite face being orientated horizontally downwards The contrast between these two faces is that the upwards facing surface receives maximum solar exposure while the downward facing surface receives no solar exposure.

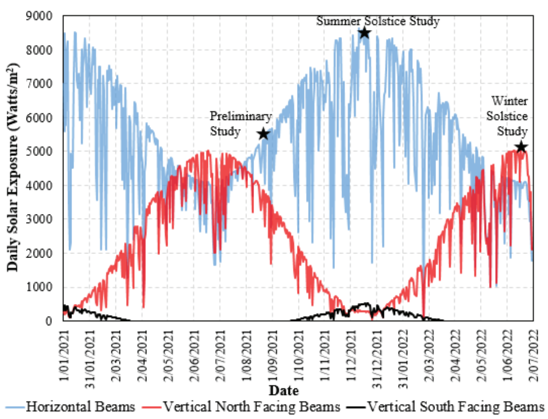

Figure 3. Daily solar radiation doses on a horizontal surface was from the Bureau of Meteorology. Vertical surface doses were calculated based on the incidence angle to the sun.

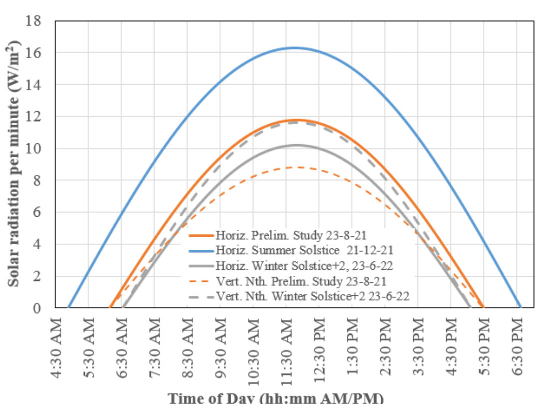

Figure 4. Horizontal and vertical north facing solar radiation per minute on each of the three trial dates.

Table 2. Summary of solar details for each measurement date.

Trial Type		Preliminary	Summer Solstice	Winter Solstice + 2
Trial Date		23rd August 2021	21st December 2021	23rd June 2022
Daily Solar Radiation	Watts/m^2	5111	8555	4111
Sunrise Time	h:mm AM/PM	6:09 AM	4:54 AM	6:33 AM
Sunset Time	h:mm AM/PM	5:33 PM	6:38 PM	5:07 PM
Culmination Time	h:mm AM/PM	11:51 AM	11:46 AM	11:51 AM
Daylight Duration	Hours : minutes	11:24	13:44	10:34
Measurements per beam	Number	8	9	11
Total measures on 44 beams	Number	352	396	484

The surface temperature of all downward facing surfaces, regardless of the surface finish, was measured and corresponded to the air temperature, except for a slight lag in rising air temperature before about 9 am in the morning. This can be explained by residually lower energy below the surface corresponding to the preceding nights cooling stage of the temperature cycle. i.e. the wood is slow to heat in the morning after cooling during the night.

The impact of solar radiation on surface temperature during the day was pronounced on the upward facing surfaces, and did rise and fall based on the solar radiation exposure of the surface at the measurement times. The increases in upward facing surface temperature throughout the day can be seen in Figure 5 for each of the three days evaluated. These graphs show clearly the rise in surface temperature over and above the surrounding ambient air temperature. The black surface, in all cases showed the highest rise in surface temperature. The peak temperature increase for the black surface was 19.7 degrees Celcius above the ambient air temperature of 34.1 degrees Celcius at 11:45 am on the 21/12/21. The white surface, in all cases had the lowest temperature and during the shortest solar exposure day, the surface temperature was close to the ambient air temperature. The unfinished and epoxy finished wood surfaces, both with a natural wood colour, were intermediate with an increased temperature between the black and white surfaces.

3.3 Radiata Pine – Predicted Temperature

The surface temperature of the radiata pine beams with the four different surface finishes can be modelled through the application of equation (4) with knowledge of the air temperature, the solar radiation at the time of measurement, the convection heat transfer coefficient in air and the solar absorptance of the surface. The air temperature used in the model was from Australian Government Bureau of Meteorology Weather Station (ID 040405) which measures air temperature at about 30 minutr intervals. The solar radiation at the trial site was determined from the solar irradiance reported at the same weather station. This daily dose value was then apportioned throughout the trial days based on knowledge of the sunrise and sunset times assuming a symmetrical sinusoidal radiation distribution, with a peak radiation at the culmination time.

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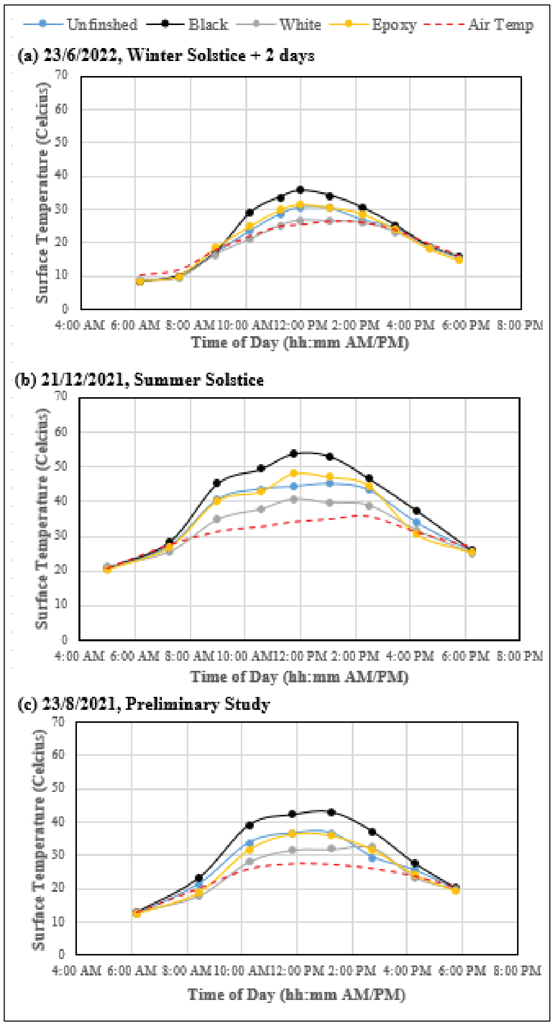

Figure 5. Upward facing radiata pine beam surface temperatures (Celcius) throughout the exposure days. A) 23/6/2022 Winter solstice, b) 21/12/21 Summer solstice, c) 23/8/21

Figure 4 shows the distribution of solar radiation for the horizontal and north facing surfaces. The convection heat transfer coefficient was determined by averaging the wind speeds for the daytime periods at each trial date at the nearby weather station. These average wind speeds were between 12.7 km/hr and 14.0 km/hr. Using a known empirical relationship [14] between wind speed and convection heat transfer in air [15], heat transfer coefficient values from 29.8 to 30.5 watts/m^2.Celcius were determined. A heat transfer coefficient value of 30 was used to predict the surface temperature for all surfaces on all three trial days. A linear optimization procedure was used to estimate the solar absorptance for each surface. Table 3 shows the solar absorptance estimate (scale 1-0) to be 0.81 for the black surface, 0.36 for the white surface, 0.55 for the unfinished surface and 0.61 for the epoxy finished surface. Predicted surface temperatures for each of the three days and each of the four surfaces were estimated and compared to the actual surface temperatures measured for each surface. Table 3 summarizes the surface temperature predictions across the three days, and compares these with the 28 measured actual temperatures at these times.

Table 3. Radiata pine beams. Surface temperature comparisons. Actual and Predicted.

Surface Finish		Black	White	Unfinished	Epoxy
Solar Absorptance (1-0)		**0.81**	**0.36**	**0.55**	**0.61**
Actual Temperature (C^{0})	Average	30.9	25.4	27.7	27.7
	Maximum	53.8	40.7	45.2	48.1
	Minimum	8.2	8.8	8.4	8.4
	Range	45.6	31.9	36.8	39.7
Predicted Temperature (C^{0})	Average	34.1	27.5	30.2	31.2
	Maximum	60.1	44.1	50.7	53.0
	Minimum	12.5	11.6	12.1	12.2
	Range	47.6	32.5	38.7	40.8
Actual – Predicted Relationship	Correlation Coefficient	0.94	0.96	0.96	0.96
	R^2	0.89	0.92	0.91	0.92
	Slope	0.98	1.03	1.01	0.99

In summary, the predicted average surface temperatures of the radiata pine beams are about 10% greater than the actual temperatures measured at each time for each surface. The coefficient of determination for the predicted surface temperature versus the actual surface temperature for the different surfaces is about 0.91. The differences between the climatic variables measured at the nearby weather station and those experienced by the beams at the trial site may explain some of the variation. i.e. solar radiation, air temperature, wind speed. Differences may also occur because of topographical, vegetative and microclimatic differences between sites. Assumptions about the solar distribution throughout the day may also account for some variation. The relative simplicity of the model applied can also potentially account for differences.

3.4 Hybrid Pine – Actual Temperature

The measured temperatures of the hybrid beams were averaged for each set of beams at the same measurement time and for each orientation. A total of 6 unfinished beams for each orientation were averaged, while only 2 beams of all other finishes were averaged for each orientation, as per Table 1. The increases in horizontal upward facing surface temperatures throughout the day can be seen in Figure 6 for each of the three days evaluated. The temperature of beams oriented vertically and facing south, all corresponded with the ambient air temperature. Only during the summer solstice did these vertically south facing beams receive any direct solar exposure and this was early in the morning and late in the afternoon when the sun rose and set in the southern portion of the sky. Any minor increase in surface temperature due to this minimal solar exposure has not been considered in the analysis. The vertical orientated north facing beams received higher solar exposure during mid-year when the sun was lower in the northern sky. These beams received negligible solar exposure at the summer solstice measure, as the sun rises and sets in the southern sky and at noon for the site latitude the sun is nearly vertical in the sky. The angle of incidence at noon to the vertical beams is less than 2 degrees Celcius. During the winter solstice the solar exposure on the north facing vertical beams is actually greater than the solar exposure on the horizontal beams.

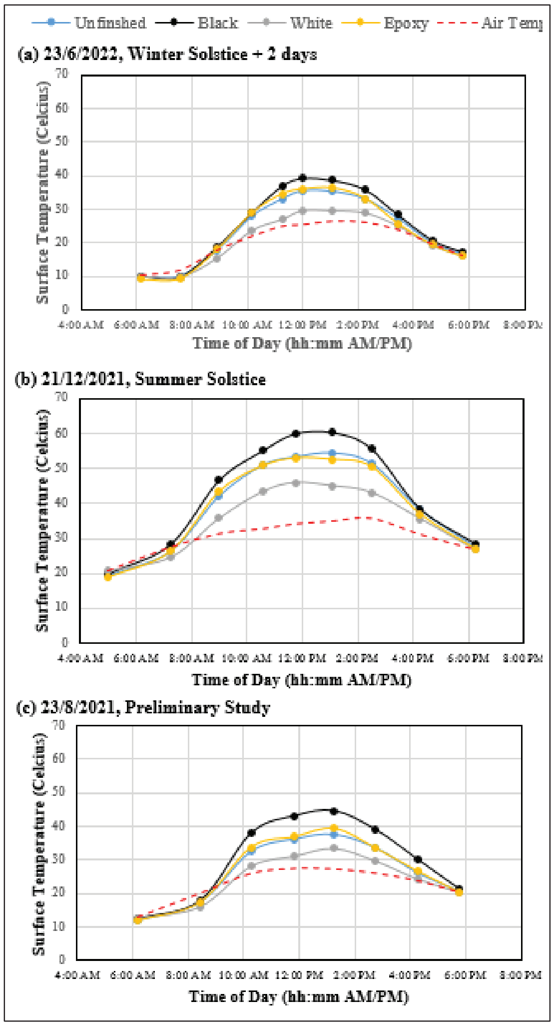

Figure 6. Upward facing horizontal hybrid pine beam surface temperatures (Celcius) throughout the exposure days. A) 23/6/2022 Winter solstice, b) 21/12/21 Summer solstice, c) 23/8/21

Figure 6 shows the rise in surface temperatures over and above the surrounding ambient air temperature, due to solar radiation falling on the surfaces. The black surface in all cases showed the highest rise in surface temperature. The peak temperature increase for the black surface was 25.9 degrees Celcius above the ambient air temperature of 34.1 degrees Celcius at 11:45 am on the 21/12/21. In all cases the white surface had the lowest temperature and during the shortest solar exposure day the surface temperature very much matched the ambient air temperature. The unfinished and epoxy finished wood surfaces, both with the natural colour of wood, were intermediate in increased temperature between the black and white surfaces.

3.5 Hybrid Pine – Predicted Temperature

The surface temperature of the hybrid pine beams with the four different surface finishes can be modelled through the application of equation (4) with knowledge of the air temperature, the solar radiation at the time of measurement, the convection heat transfer coefficient in air and the absorptance of the surface. The same modelling approach as used for the radiata pine beams described in 3.3. A linear optimization procedure was used to estimate the solar absorptance for each surface. Table 4 shows the solar absorptance estimate (scale 1-0) to be 0.91 for the black surface, 0.50 for the white surface, 0.73 for the unfinished surface and 0.76 for the epoxy finished surface. Predicted surface temperatures for each of the three days and each of the four surfaces were estimated and compared to the actual surface temperatures measured for each surface. Table 4 summarizes the surface temperature predictions across the three days, and compares these with the 28 measured actual temperatures at these times.

3.6 Observations

Observation of the surface condition of both the radiata pine and hybrid pine beams were made. i.e.

1. The radiata beams surface condition for all finishes showed no difference between the three measures.

2. The hybrid beams showed general darkening from the natural wood colour towards a dull yellow colour.

3. The hybrid beam surfaces showed some darkening from surface mould growth. This was most noticeable at two distinct times during the 18 month exposure trial. In general, mould events occurred following extended periods of very high relative humidity. The southern exposed beams were more affected by mould relative to the more sun exposed beams in the horizontal and vertical north beams.

4. The hybrid beams facing south showed some surface greying over time.

5. Some lightening or “washing” of the initial wood colour of the hybrid beams occurred on the horizontal beams, with a spacing of about 70 to 80 mm.

6 Some darkening of surfaces with dissolved wood extractives has occurred on the hybrid beam surfaces. This extractive stain occurred on horizontal beam surfaces and shows a spacing between lighter areas at a frequency of about 70 to 80 mm.

7. Epoxy finishes on the hybrid beams showed deterioration with flaking and peeling observed. Regions with a thinner coating are more affected than regions with a thicker coating

Table 4. Hybrid pine beams. Surface temperature comparisons. Actual and Predicted.

Surface Finish		**Black**	**White**	**Unfinished**	**Epoxy**
Solar Absorptance (1-0)		**0.90**	**0.50**	**0.73**	**0.76**
Actual Temperature (C^0)	Average	31.9	27.2	29.7	29.5
	Maximum	60.3	46.0	54.4	53.0
	Minimum	9.9	9.8	9.8	9.3
	Range	50.5	36.2	44.6	43.8
Predicted Temperature (C^0)	Average	33.7	28.2	31.4	31.8
	Maximum	59.5	46.4	54.0	54.9
	Minimum	12.6	12.0	12.4	12.4
	Range	46.9	34.3	41.6	42.4
Actual – Predicted Relationship	Correlation Coefficient	0.93	0.92	0.93	0.94
	R^2	0.86	0.84	0.86	0.88
	Slope	0.97	0.99	1.00	0.99

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8. The black stain finish on the hybrid beams appears to have become slightly more transparent with increased exposure.

9. Pre-existing bluestain in hybrid beam laminates, which was visible through initial surface finishes, faded with exposure.

In summary, the colour of all surface finishes was affected by exposure. Figure 7 shows 0, 12 and 18 month exposed beams adjacent to each other. These images highlight some of surface changes observed. The summer solstice measures correspond approximately to the 12 month exposure images shown while the winter solstice images correspond to the 18 month exposure images.

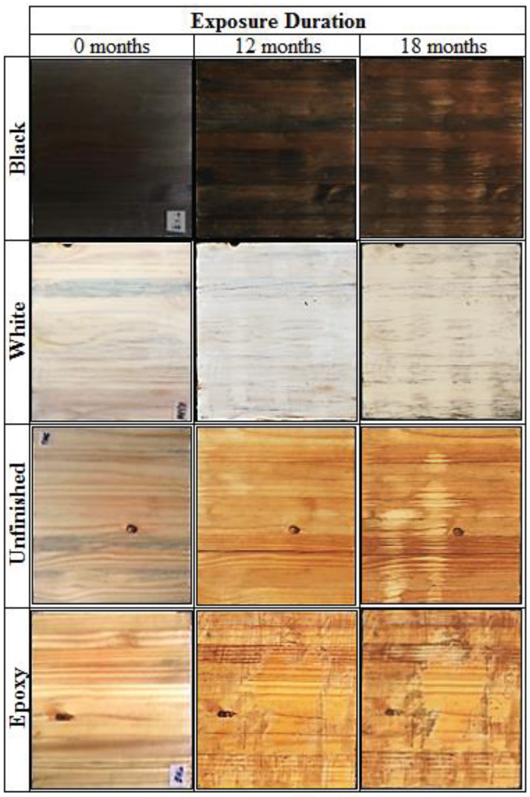

Figure 7. Surface images for 0, 12 and 18 months from start of exposure for horizontally exposed hybrid pine beams.

4 – DISCUSSION

The optimization objective used with the described surface temperature model was to estimate a surface absorptance value which would achieve a 1:1 relationship (slope approximates 1) between the actual and the predicted temperatures, for individual combinations of exposure, beam type and orientation, and for each surface finish type. The absorptance value used to then predict a surface temperature was determined by finding a weighted average of the individual surface values found for each exposure condition. Some of the differences between the predicted and actual temperatures (Tables 3 and 4) can be explained by the simplified model adopted, with the associated assumptions of zero energy loss into the wood via conduction and out of the wood via radiation. Indirect solar radiation, including diffuse and reflected solar radiation acting on the surface was also assumed to be zero. A more detailed summary of the individual absorptance values found for each combination of exposure, beam type, surface orientation and finish type is shown in Table 5.

Assuming that the radiata beam absorptance values determined with less than 3 days of exposure, represents the "as new" absorptance of the finish and that there is no inherent species difference between radiata pine and hybrid pine, then a general trend showing the change in surface absorptance due to exposure can be examined by plotting all absorptance values against the date of exposure at each measure. These trends are shown in Figure 8, which indicates that the absorptance of all four finish types increases as the length of exposure increases. Surface changes causing some darkening as noted in 3.6 Observations, may explain this increase.

A comparison of the absorptance values found in this study with the typical absorptance values for different surfaces, listed in the explanatory information of the Building Fabric provisions of Australia's National Construction Code [9], is shown in Table 6. This comparison highlights the similarities in absorptance values between the values based on standard testing [16] and the four surface finishes selected in this study. The ASTM method [16] for determining the absorptance of opaque materials uses an integrating sphere spectrophotometer apparatus and applies Kirchhoff's law of thermal radiation. The method used in this study differed from the standard laboratory method, as it included the impact of air flow across the surface as well as assumptions about heat acting on the glued laminated timber.

The observations of surface condition warrant some discussion.

The internal no light storage conditions adopted between the three measurement events for the radiata beams appears to have maintained these surfaces in an "as new" condition.

Table 5. Calculated absorptance values for each combination of exposure, beam type and surface orientation.

Exposure	Beam Type	Beam Exposure Orientation	Daily Solar Radiation	Measure Time	Days Exposed	Calculated Solar Apsorbtance (0-1)			
			Watts/m^2	Date	No.	**Black**	**White**	**Unfinished**	**Epoxy**
Discrete	Radiata	Horizontal Upwards	5111	23/08/2021	0	0.86	0.38	0.59	0.58
			8555	21/12/2021	1	0.76	0.33	0.52	0.6
			4111	23/06/2022	2	0.82	0.37	0.55	0.63
					Weighted Average	**0.81**	**0.36**	**0.55**	**0.61**
Continuous	Hybrid Pine	Horizontal Upwards	5111	23/08/2021	234	0.86	0.39	0.6	0.66
			8555	21/12/2021	354	0.96	0.49	0.79	0.79
			4111	23/06/2022	538	0.94	0.49	0.79	0.85
		Vertical North Facing	3811	23/08/2021	234	0.90	0.56	0.67	0.72
			279	21/12/2021	354	Negligible exposure. Sun near vertical at noon.			
			4683	23/06/2022	538	0.86	0.54	0.77	0.75
		Vertical South Facing	0	23/08/2021	234	No solar exposure			
			negligible	21/12/2021	354	Negligible exposure. Early morning and late afternoon sun only.			
			0	23/06/2022	538	No solar exposure			
					Weighted Average	**0.90**	**0.50**	**0.73**	**0.76**

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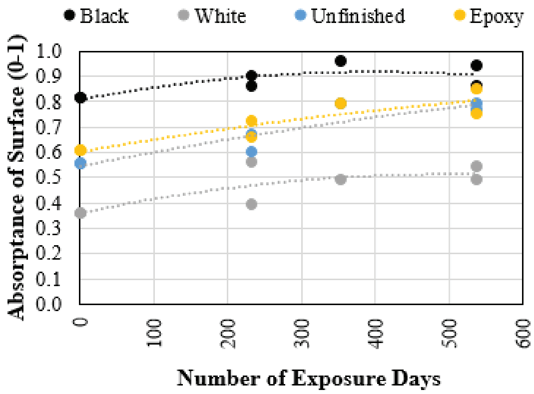

Figure 8. Measure date versus solar absorptance for each finish, assuming no species differences between Radiata and Hybrid Pine.

The natural darkening of wood which has occurred may be due to enzymatic oxidation [17] of wood and/or ultra violet radiation induced photodegradation of wood.[18]

The darkening from water staining may be explained by vapour condensation, which was observed during the 18 month trial. Water soluble wood extractives may accumulate on exposed surfaces following evaporation of any free surface moisture. The protective 0.8 mm clear polycarbonate sheet used to keep precipitation from directly making contact with surfaces has a sinusoidal profile with a peak to peak distance of 76mm. Condensation did occurr occasionally on the lower side of this sloping clear sheet and this moisture could gravitate towards the lower points on the profile, and if of sufficient quantity, drip free water directly onto the timber surface, before any vaporization or drainage of this moisture could occur. It is considered likely that this has occurred on the horizontal hybrid beams during this trial, potentially causing both the lightened areas with less extractives and the darker areas with more extractives. This is most evident in the 18 month images in Figure 7. The increased surface mould on the white horizontal surfaces at 18 month duration, indicates sufficiently high moisture contents to facilitate the dark mould growth at a frequency corresponding to the profile of the polycarbonate protective sheet. The 18 month black hybrid beam also shows some light and dark regions at this frequency suggesting some black stain may have been mobilized by free moisture creating the colour disparity.

A number of processes seem to be involved in changing surface characteristics over the exposure period. These may include biological, chemical, physical, leaching and thermal mechanisms. The individual impacts of such changes on surface temperature has not been determined in this study, however some combined impact of these mechanisms is reflected in the absorptance values shown in table 5 and figure 8.

Absorptance, is a somewhat nebulous surface characteristic of glued laminated timber due to (i) the natural colour variations of a wood surface, (ii) variation from the application of a surface finish on a glued laminate surface, and (iii) the changes in absorptance which may happen during exposure, due to a range of

Table 6. Comparison of solar absorptance values (0 – 1) between typical values (ABCB 2016) and the values for the four finishes on the radiata beams in this study

Absorptance values (ABCB 2016) based on ASTM E903 (2012)		Absorptance values from this study (Radiata Pine Beam)		
Colour	Value (0-1)	Wood Surface - Finish	Average (0-1)	Range (0-1)
Slate (dark grey)	0.90			
	0.85			
	0.80	Black spirit based	0.81	0.76 - 0.86
Red, green	0.75			
	0.70			
	0.65			
Yellow, buff	0.60	Clear epoxy finish	0.61	0.58 - 0.63
Zinc aluminium — dull Galvanised steel — dull	0.55	Unfinshed	0.55	0.52 - 0.59
	0.50			
Light grey	0.45			
	0.40			
Off white	0.35	White oil based stain	0.36	0.33 - 0.38
Light cream	0.30			
	0.25			

deterioration mechanisms. This nature of absorptance may need consideration when designing the integrity of a glued laminated timber surface.

5 – CONCLUSIONS

A field study of 44 glued laminated pine surfaces with four different finishes, exposed in sub-tropical Australia to outdoor undercover conditions, has provided information to assist in predicting surface temperature. The following conclusions are made from this study.

1. The surface temperature of glued laminated timber in exposed outdoor undercover applications will change in response to, i) air temperature, ii) air speed, iii) solar radiation, and iv) the solar absorptance of the finished surface.

2. Absorptance provides a good relative means of quantifying the energy absorbed by a surface and thus the relative change in surface temperature which may occur during the course of environmental cycles, be that daily, seasonally, yearly or climatic event based. Black, with a high absorptance can be expected to reach higher temperatures than natural coloured timber surfaces, while white surfaces will show relatively less temperature increase.

3. The absorptance of glued laminated timber surface finishes may show increases as the duration of exposure increases, at least up to the 18 month duration of this trial. The darkening of surfaces due to biological action, natural wood darkening via oxidation or photodegradation, and via surface leaching-accumulation of dark coloured water soluble wood extractives, may all increase the surface temperature of glued laminated timber in outdoor undercover applications.

4. A simple model based on energy equalization of radiation heating and convection cooling can be used to estimate the surface temperature of glued laminated timber in outdoor undercover applications.

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