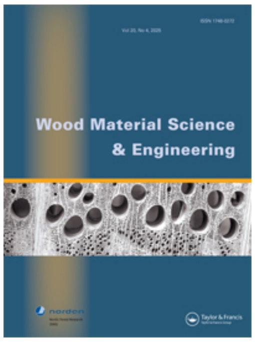

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A hazard map for surface splits in outdoor undercover unfinished glued-laminated timber

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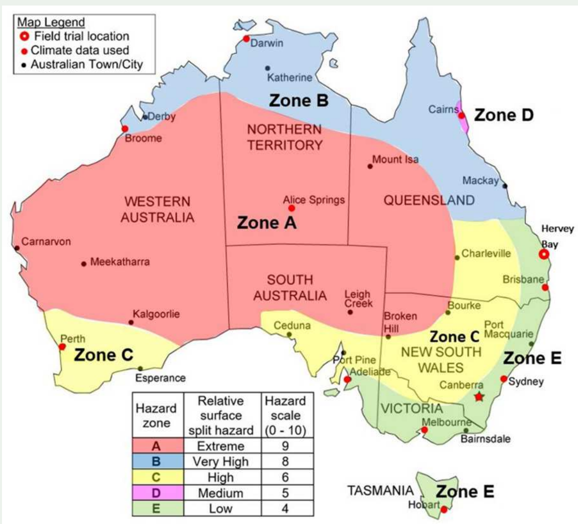
ABSTRACT

An Australian hazard map is proposed for surface splits in unfinished horizontally oriented glued laminated timber exposed to outdoor undercover climatic conditions, excluding precipitation. A 69 d field trial of four glued laminated timber surfaces in subtropical Australia determined the daily climatic variables contributing to the occurrence and development of surface splits in both laminates and gluelines. An empirical surface split index (SSI) is proposed using daily 3 pm measurements of both air temperature and relative humidity, as well as solar exposure calculated at 3 pm. Days with a calculated SSI of less than six were associated with the occurrence of new surface splits in glued laminated timber surfaces, whereas days with an SSI greater than six corresponded to the opening or closing of existing surface splits. The proposed SSI algorithm was applied to daily climate data from 2010 to 2021, for 12 Australian weather stations. Distinct SSI differences between stations allowed grouping of weather locations with similar SSI results. This grouping led to the proposal of a five-zone surface split hazard system for Australia, and a surface split hazard map for Australia. The uncertainties associated with the proposed map and its application are discussed.



Proposed surface split hazard zones in Australia.

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KEYWORDS
Wood; surface splits; hazard zone; solar radiation; relative humidity; air temperature

1. Introduction

The exposure of glued laminated timber to outdoor undercover service conditions can result in surface deterioration due to the action of environmental agents. Commonly referred to as "weathering," multiple deterioration agents may be involved, including thermal, biological, mechanical, physical, and chemical mechanisms (Williams 2010). Longitudinal surface fractures are a type of deterioration characteristic of weathered timber surfaces and can occur in the wood itself or gluelines. These types of fractures are usually oriented along the grain, with a relatively narrow width perpendicular to the grain and some depth into the surface on which they occur. The length of these fractures is usually the most observable and measurable characteristic. The perceived randomness of occurrence over time and the magnitude of a fracture may be disconcerting, even for experienced observers. Some fractures may be sufficient in magnitude and distribution to adversely impact the structural, fire, durability, and/or aesthetic performance of

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a surface. The increasing use of glued laminated timber surfaces in larger sizes, expressed externally in structures to show the natural characteristics of wood has elevated the importance of surface integrity. Surface fractures are explained due to changes in atmospheric conditions that cause moisture gradients in the wood and induce surface stresses (Peck 1957, Franke and Franke 2014). Moisture gradients are induced by the movement of moisture in/out of wood, as it strives to achieve an equilibrium moisture content (EMC) with atmospheric moisture. The diffusion of moisture in wood is also influenced by temperature (Siau 1984), with moisture diffusion increasing as the kinetic energy of the particles increases. Solar radiation also has the potential to raise the wood temperature, thus influencing moisture diffusion, which in turn contributes further to shrinkage strain gradients. In this study, in-service environmentally induced surface fractures are referred to as "surface splits," rather than fractures, cracks, checks, fissures, or other terms, which may have different connotations or imply causal mechanisms. Figure 1 shows typical surface splits in exposed glued laminated timber.

Material specifications, surface finishes, solar shielding, ~~and~~ inspection and maintenance practices are some of the strategies typically used to minimize surface split development in glued laminated timber elements in service. A study of unfinished glued laminated timber to assess the inherent surface split hazard of a locality and its climate, regardless of any protective strategy, is the basis of the reported research. In this study, "unfinished" means timber surfaces in a raw prefinished state with only machine dressing having been applied, and no additional surface products. Unfinished timber has the potential to exaggerate surface splits arising from climatic variables and to provide a reference performance level for the influence of regional climate on this deterioration characteristic.

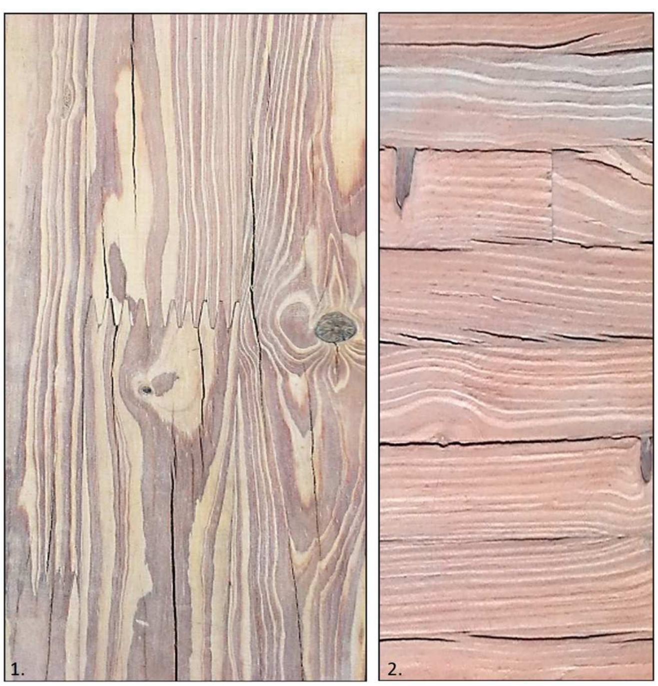

Figure 1. Typical surface splits in exposed glued laminated timber manufactured from Australian grown plantation softwood. This surface has an oil based white stain finish applied. 1. backsawn laminate faces with surface splits in laminates. 2. quartersawn laminate faces with surface splits at or near gluelines.

Hazard maps are useful tools for conveying information about regional hazards, which may cause structural element failure either via a deterioration agent or via a load action, thus impacting service life and/or causing structural failure. A hazard map can convey regional information regarding the relative or quantifiable risk of a hazard event, that assists structure designers and others to meet requirements concerning the probability of structural failure and/or a specified service life. The establishment of a particular hazard for a structure or element thereof is necessarily followed by appropriate design, construction, or maintenance decisions to eliminate, minimize, and/or control the potential impact of a destructive agent or mechanism.

Environmental agents impacting upon a structure's performance may be shown geographically in a hazard map. Australian structure designers are familiar with hazard maps concerning wind actions (Standards Australia 2021), earthquake actions (Standards Australia 2007) and snow and ice actions (Standards Australia 2003). Hazard maps are also used in the durability design of structures. For example, hazard maps are used to understand the potential deterioration from termites, embedded corrosion of metals in timber, atmospheric corrosion of metal connectors in timber due to coastal salt, or from marine borers (Forest and Wood Products Australia 2012). Hazard maps are also used for above ground and in ground decay (Forest and Wood Products Australia 2012, Queensland Department of Agriculture and Fisheries 2020). Biological degradation hazard maps for wood use in Europe are also receiving increased attention as climate changes potentially extend deterioration organisms (van Niekerk 2022). This study noted that hazard maps are essential for service life planning and with potential to reduce the number of prematurely failing wooden structures.

A study of moisture induced stresses perpendicular to grain (Fragiacomo *et al.* 2011) involved the modelling of moisture gradients in Norway Spruce, for sawn timber, glued laminated timber and cross-laminated timber. This study used a finite element model to input the air temperature and relative humidities from several European climates, and found that variation in moisture content can result in stresses that would probably cause cracking in uncoated timber. This study concluded that Northern European climates were found to result in higher moisture gradients and thus in higher moisture-induced stresses when compared with Southern European climates. This study provides evidence of regional climates potentially acting on timber surfaces to cause cracking. An obvious extension of this study would be a climate induced cracking map for Europe.

The relationships underpinning durability hazard maps may be established via field trials or knowledge of an agent's optimal climatic conditions for growth. Assuming that surface splits in glued laminated timber are primarily caused by the action of air temperature, relative humidity, and solar radiation on timber surfaces, it is hypothesized that regional hazard information for surface split occurrence could be displayed in a map. The objective of this study was to explore this hypothesis and propose a method for developing a hazard map for surface splits.

2. Materials and methods

The research strategy used assumes that surface splits can be explained using knowledge of daily climatic conditions only. The logic for this assumption is that the likely climatic conditions (temperature, relative humidity, and solar radiation) influencing surface split occurrence and development can all exhibit extremes within a daily cycle. For instance, there is no solar radiation at night and maximum solar radiation when the sun reaches its peak elevation at solar noon. Similarly, the sun heats air masses during daylight hours, resulting in peak atmospheric temperatures after noon, with minimum daily temperatures generally occurring the hour before sunrise, following a cooling phase during the night. Atmospheric moisture is strongly influenced by air temperature, with relative humidity increasing in colder air and decreasing in warmer air. The relative humidity of the atmosphere typically reaches a daily peak corresponding to the minimum air temperature at night and conversely a minimum at the maximum air temperature after noon. This alignment of the diurnal variation of these three likely climatic variables is assumed to stimulate surface split occurrence and development.

A trial design was developed to examine the influence of these daily climatic variables on the occurrence and development of surface splits in glued laminated timber. A horizontal surface orientation was selected, as this is the standard measurement plane for solar radiation reaching the Earth's surface. It is also the plane subject to the greatest solar radiation for most of the year at the trial site, and is therefore likely to exaggerate any surface splits.

The timber used in the trial was a hybrid *pinus* species developed and grown in plantations in Queensland, Australia. Specifically, it is a locally developed hybrid of slash pine (*Pinus elliottii var. elliottii*), and Caribbean pine (*Pinus caribaea var. hondurensis*). This resource is used commercially in Queensland, Australia, to manufacture timber products, including glued laminated timber. The timber used in the trial was sourced from an earlier resource characterization study (Bailerres et al. 2019). This timber had been stored in dry open under cover conditions for several years in Brisbane (250 km south of the trial site), with good acclimatization to ambient environmental conditions. Sawn sections approximately 100 × 38 mm in size were selected to have a stratified and wide distribution of typical surface characteristics. A total of 18, 1.8 m long pieces were selected and sorted into two groups based on sawing orientation, referred to as tangential or radial sawn. This was done to reflect marketplace manufacturing practices where adjacent laminates often have similar sawing orientations. A commercially available polyurethane (PUR) adhesive (Loctite HB S309 Purbond) was used to manufacture two beams. All trialled beam surfaces were nine laminations wide with individual laminates of 32.3 mm in thickness. Each of the two beams (tangential and radial) was then docked to provide four beams 210 mm in length and 290 mm in width.

Figure 2 shows the cross-section of each beam and the initial unexposed surface of all four beams, with their identifying specimen labels, FR2, FR3, FT2, and FT3. Each of the two sets of tangential and radial sawn laminated beams contained matched wood samples to ensure that any observed surface split differences were not due to wood variability. Following manufacture, the average density and average moisture content of the tangential laminate beams were measured as 622 kg/m^3 and 9.9%, respectively, while those of the radial laminate beams were measured as 539 kg/m3 and 10.0%, respectively. The trial beams were sealed to restrict moisture movement on all surfaces, except the surface intended for exposure. The beam ends, sides, and backs were sealed with a two-part polyester resin applied directly to the wood surface, followed immediately by a 0.63 mm aluminium foil applied to the tacky resin prior to its hardening. This stuck the foil to the unexposed beam surfaces, providing a barrier to moisture transfer, which minimized any potential impact from the five sealed faces on the exposed study surface.

The four trial beams were exposed to a subtropical environment located in Queensland, Australia, at a latitude of −25.3061° and a longitude of 152.8710°. The exposure site is 20 m above sea level and is located 2 km from an Australian Government Bureau of Meteorology (BOM) weather station (No. 040405) at a latitude of −25.32°, longitude of 152.88° and height of 13 m. The climate in this region is classified as humid subtropical, characterized by hot and humid summers and cool to mild winters (Peel *et al.* 2007). About 20% of the world's population live within this type of temperate zone with no dry season (Mellinger *et al.* 1999). This represents major climatic regions on all continents, except Antarctica. All four trial beams were supported at least 400 mm above the ground, with open ventilation to all exposed surfaces.

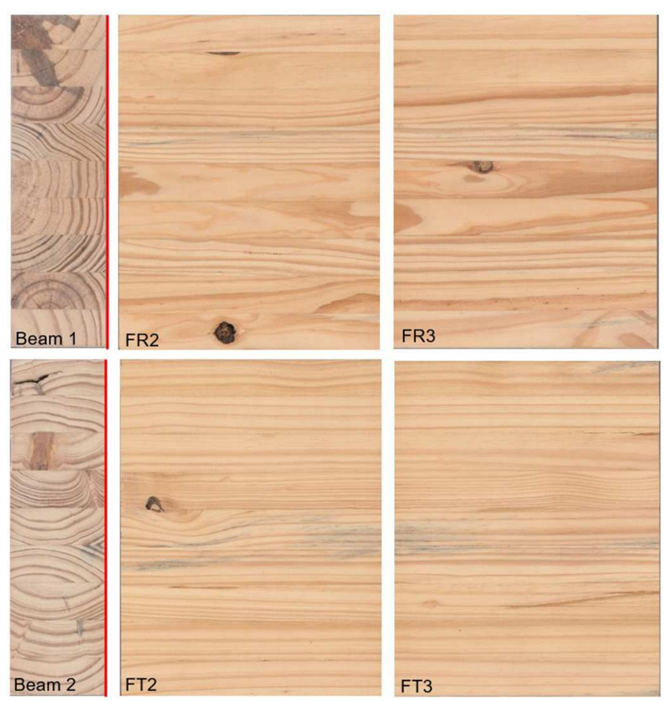

Figure 2. Four trial beams, cross sections on left and initial unexposed unfinished surfaces on right. The red line indicates the exposed face. Beam 1. Radial faced beams FR2 and FR3, Beam 2. Tangential faced beams FT2 and FT3.

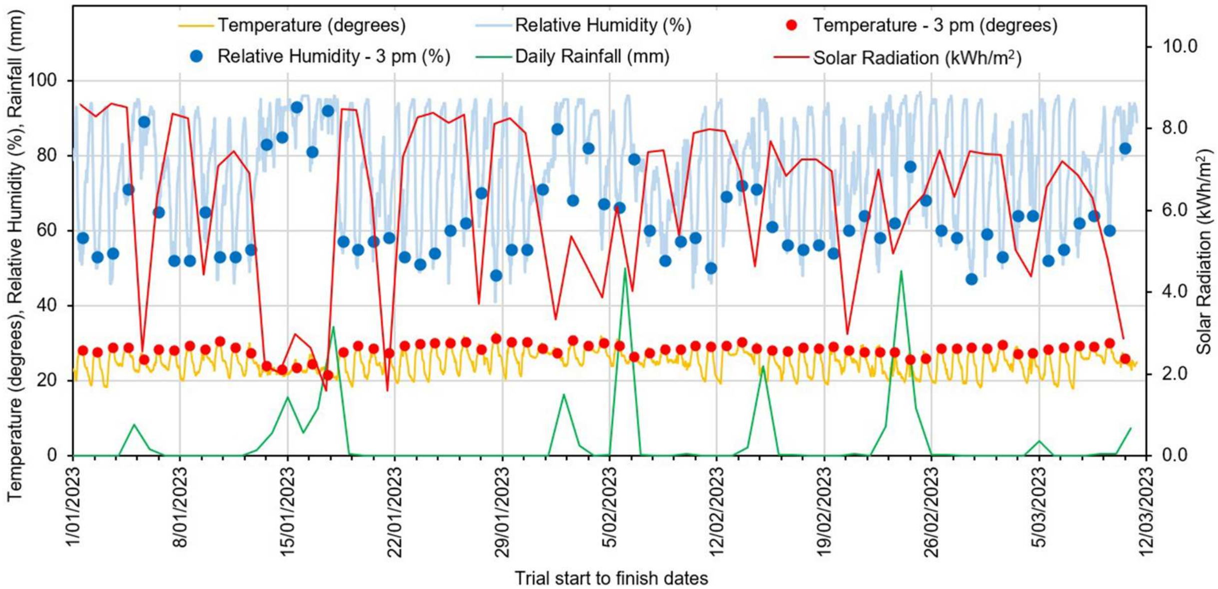

Figure 3. Summary of major climatic measurements for the trial period. 1st of January 2023 – 10th of March 2023.

Protection from direct precipitation was from a 0.8 mm clear polycarbonate profiled roof sheet, positioned about 200 mm above the four beams and overhanging both by at least 300 mm.

The Bureau of Meteorology data for the nearby weather station (No. 040405) was collected from half-hourly measurements of the relative humidity, temperature, and rainfall. Daily climate summary information was also collected, including temperature (maximum, minimum, 9 am, 3 pm), relative humidity (9 am, 3 pm), rainfall, wind speed and direction (maximum, 9 am, 3 pm), cloud cover score (9 am, 3 pm), and mean sea level pressure (9 am, 3 pm). The daily solar radiation at this weather station was also collected. The exposure trial commenced on the 1st of January 2023 and ceased on the 10th of March 2023, after 69 days of exposure. Figure 3 shows the changes in the temperature, relative humidity, rainfall, and solar radiation over the trial period. These climatic conditions are typical of this location for this time of year.

Surface split occurrence was determined in each laminate of each of the four beams by visual means, where distinct separation between adjacent sides of a split was detected using human vision. Human stereoscopic vision can discriminate binocular disparities as small as 2 s of arc (Kane *et al.* 2014). At a distance of 200 mm, the inspection distance used in this study, this represents a split width of 0.005 mm. The presence of a split gap of at least this width constituted the occurrence of a split and governed its length limit. Splits less than this width are likely to be discerned as a line on the surface and are not considered in this study. Surface split length was measured to the nearest 5 mm using a conventional steel tape measure with 1 mm increments. Visual assessment was the methodology for both split occurrence and length measurement, as this corresponds to human appraisals made in real structures by occupants, owners, builders, designers, and material suppliers. The author's eyes with reading glasses were the visual assessment tool used in this study. All measurements were performed in ambient daylight, between 2 pm and 4 pm. Digital images of each surface at each inspection were obtained and used for reference purposes only.

Surface split width and depth were not assessed in this study because of the smaller dimensional scale of these characteristics, lower accuracy associated with measuring such small values, variation in both width and depth along the split, and difficulty in accurately measuring the split depth. It is assumed that the split length is a general indicator of split magnitude. Surface splits were also evaluated based on their location within the glued laminated surface. Splits wholly contained within a wood laminate were aggregated by summing individual split lengths within a beam, and reporting these as laminate splits. Splits at or within 5 mm of a glueline were separately aggregated by summing individual split lengths within a beam, and reporting these as glueline splits. The aggregate split length and aggregate number of splits for both the laminates and gluelines in each of the four beams were determined at daily intervals.

3. Results

3.1. Surface split occurrence and development

Surface splits occurred in all four glued laminated timber beams, within both the laminates and at gluelines. The aggregated surface splits in the radially faced laminated surfaces were greater than those in the tangentially faced laminated surfaces. The aggregate surface split length at the gluelines was approximately 30% of the aggregate surface split length within individual laminates. Surface splits at gluelines were not used in the analysis because of the reduced split magnitude and the influence of non-climatic manufacturing variables, such as earlywood and latewood features, which were found to influence surface splits at or near gluelines. Figure 4 shows the aggregate surface split lengths in the laminates of the four individual surfaces and all four combined surfaces.

The aggregated nature of the surface split length poses an issue when correlating climatic variables in order to detect

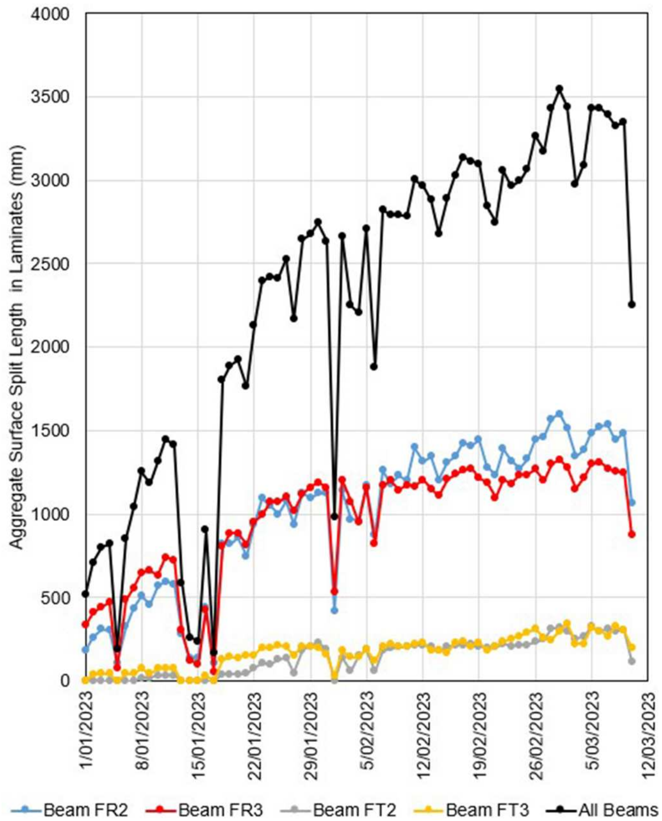

Figure 4. Aggregate surface split length in laminates for 4 beams individually and all beams combined.

causal influences. The aggregated surface splits of all four beams were transformed to a surface split ratio that reported the ratio (mm/mm) of the actual aggregated surface split length to the modelled surface split length. This negates the aggregated nature of the surface split results and facilitates an improved correlation analysis. A quadratic model was fitted to the combined aggregated surface split length for all beams over the trial period. These daily variations from the surface split trend line were assumed to better reflect daily causal climatic conditions. The differentiation between new and existing surface splits can be examined via the progression of the aggregated surface split length from day to day. In summary, three types of surface split occurrences and developments were identified for each day's results. The three types are (1) new surface splits occur, (2) existing surface splits close, and (3) existing surface splits open to less than the previous maximum surface split length. These three types are defined as follows:

1. New surface splits occur. The aggregated surface split length for a day is greater than for the aggregated surface split length for all previous individual days. It is assumed that the day's specific climatic conditions, leading up to the time of the daily measurement, were sufficient to cause an increase in surface split length, that is, new surface splits.

Where aggregated surface split length increases do not occur, it is assumed that the days' climatic conditions leading to the time of measurement have not resulted in new surface splits. Two types of surface split development are possible.

2. Existing surface splits close. The aggregated surface split length for a day is less than the aggregated surface split length for the day immediately prior, that is, some closure of the surface splits.
3. Existing surface splits open. The aggregated surface split length for a day is greater than the aggregated surface split length for the day immediately prior but less than the maximum aggregate surface split length for all preceding days.

Considering surface split occurrence and development in this way allows a general grouping of daily surface split aggregate lengths and a comparison with climatic conditions, which may result in three different types of surface splits. It also suggests a hierarchy of results that reflects conditions that may be more or less likely to cause surface splits to occur, close, or open. That is, the conditions causing new surface splits would be expected to be more severe than the conditions causing the opening of existing surface splits, and in turn, greater than the closing of existing surface splits. Figure 5 shows both the transformed results and the separation of the daily aggregated surface split length results in the three identified split occurrence or development types.

3.2 . Surface split results versus climatic conditions

While a range of climatic conditions was collected for each day of the trial, emphasis in this analysis was given to the most readily available climatic information and to the conditions

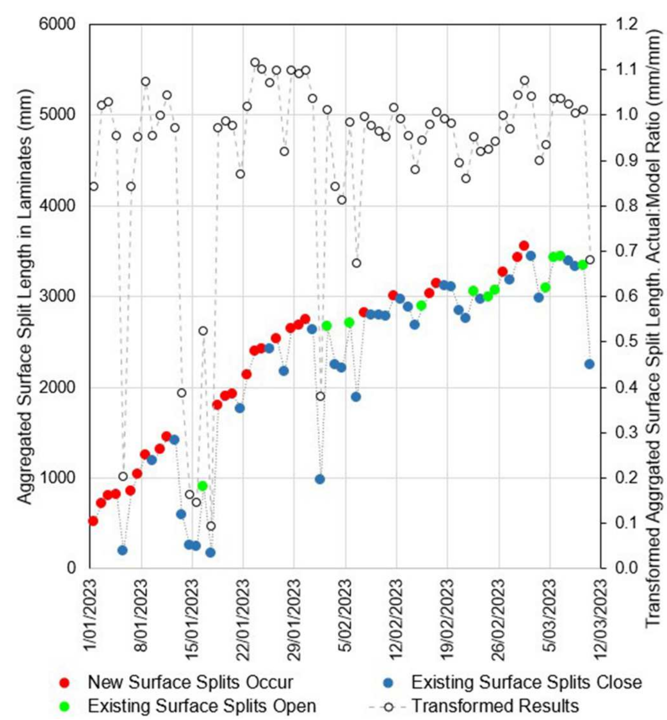

Figure 5. Transformation of data results and three types of split occurrence and development.

Table 1. Correlation analysis. Variables and surface split measures.

Split location	Linear correlation analysis		Surface split measures			
			Aggregated surface split length (mm)		Transformed surface split value (mm:mm)	
	Variables	Units	Correlation coefficient	R^2	Correlation coefficient	R^2
Laminate splits	Air temperature (3 pm)	Celsius	0.51	0.26	0.83	0.69
	Relative humidity (3 pm)	%	−0.46	0.21	−0.83	0.69
	Solar radiation (daily dose)	kWh/m^2	0.31	0.10	0.76	0.58
	Moisture content (3 pm)	%	−0.52	0.27	−0.90	0.82
Splits at bondlines	Air temperature (3 pm)	Celsius	−0.45	0.20	−0.80	0.64
	Relative humidity (3 pm)	%	0.42	0.18	0.74	0.55
	Solar radiation (daily dose)	kWh/m^2	0.29	0.08	0.69	0.48
	Moisture content (3 pm)	%	−0.51	0.26	−0.87	0.75

that appear to have the most influence on the occurrence and development of surface splits. These three climatic variables were relative humidity, temperature, and solar radiation. In general, drier, hotter conditions with higher solar radiation result in increased surface splits, whereas wetter, cooler conditions with low solar radiation result in fewer surface splits. Wood is hygroscopic and is known to vary in moisture content in response to the surrounding relative humidity and temperature, with the resulting moisture content of wood under different conditions being reliably modelled (Simpson 1973). The solar radiation acting on a horizontal surface reaches a daily maximum when the sun is at its highest point in the sky. It is also known that the air temperature reaches a peak at approximately the same time or shortly afterwards, given the heating of air masses and the additional radiation from heated surfaces in the environment. Figure 3 shows that the relative humidity is at a minimum at approximately the same time as the air temperature is at its maximum.

In Australia, two key times during a daily cycle are used to report air temperature and relative humidity. These times are 9 am and 3 pm and are available for BOM weather stations throughout Australia. The air temperature at 3 pm, relative humidity at 3 pm, moisture content at 3 pm, and daily solar radiation were selected for a correlation study with both aggregated and transformed surface splits. Refer Table 1. The moisture content value used in the correlation was calculated using an algorithm that combines temperature and relative humidity (Simpson 1973, Glass and Zelinka 2010).

3.3. Surface split index algorithm development

The correlation analysis in Table 1 provides evidence that air temperature, relative humidity, and solar radiation influence the occurrence and development of surface splits in glued laminated timber. The suggestion of moisture content is not unexpected, as changes in wood moisture content are known to cause dimensional changes owing to shrinkage strain. When shrinkage strain is sufficiently large, it can result in stress perpendicular to the grain, that may exceed the strength of the wood surface, resulting in surface splits. The additional climatic variable of solar radiation can cause a radiation based temperature increase in wood surfaces over and above the surface temperature owing to air temperature convective exchange. One approach to combining all three of the identified climatic variables would be to total the two surface temperatures (solar radiation and air convection) and then use a known algorithm (Simpson 1973) to combine the relative humidity with this summed surface temperature. This would not estimate the moisture content, but rather a possible index value that may be useful in predicting the surface split occurrence from these variables.

An estimate of a 3 pm temperature increase in the wood surface temperature, due to solar radiation alone, may use a thermodynamic approach (Stringer 2025) as follows: (1) Assume a sinusoidal distribution of solar radiation throughout the day and estimate a 3 pm solar radiation value based on this distribution, (2) assume a steady state thermodynamic system, a solar absorptance value for the surface, and a heat transfer coefficient to estimate the temperature increase due to solar radiation, and (3) sum the reported 3 pm air temperature and the calculated solar radiation induced surface temperature to estimate the total surface temperature. The proposed algorithm used to develop a surface split index for a specific day's climatic conditions is summarized in Table 2. The 3 pm air temperature is the dry-bulb temperature measured at 3 pm by a thermometer freely exposed to air but shielded from radiation and moisture. The 3 pm relative humidity is a measure of air moisture content at 3 pm. It is the ratio of the amount of moisture in the air to the maximum amount of moisture that the air can hold at the same temperature. Daily solar exposure is the amount of solar energy reaching a location on Earth's surface on a specific day. It is estimated using hourly visible radiation information from geostationary meteorological satellite imagery. The proposed calibration factor of 2.93, shown in Table 2 and applied to the total surface temperature, is an optimized value determined via the correlation of the transformed surface split value and the calculated surface split index for 69 days of the field trial. The empirically derived surface split index is shown without units, as it is intended to be a relative value useful for identifying locations with daily climatic variables that influence surface split occurrence and development in unfinished glued laminated timber.

3.4. Interpreting the surface split index

The intent of the proposed surface split index is to provide a relative daily indication of the potential for surface split

Table 2. Summary of proposed algorithm to calculate surface split index (SSI).

Input	1	Daily solar exposure (MJ/m^2)	Air temperature at 3 pm (°C)	Calibration factor (no units)	Relative humidity at 3 pm (%)
Calculations	2	Convert to kWh/m^2 (at 3pm)	|	|	|
	3	Solar radiation induced temperature, from thermodynamics (Stringer 2025)	V	|	|
	4	Combined timber surface temperature (3 pm)		V	|
	5	Weighted surface temperature (3 pm)		x 2.93	V
	6	Apply Simpson (1973) algorithm as described in Glass and Zelinka (2010)			
Output	7	Surface split index (for a single day at BOM site)			

Table 3. Surface split index (SSI) values corresponding to split types.

Statistic		Surface split type from trial		
		New Splits	Existing splits	
			Opening	Closing
Number of days of each split type		26	11	32
Surface split index value	Minimum	3.4	5.2	4.8
	Quartile 1	4.6	6.0	6.1
	Median	4.9	7.1	7.4
	Quartile 3	5.6	7.8	10.8
	Maximum	7.2	12.3	18.1
	Average	5.1	7.4	8.7
	Std. Dev.	0.9	2.1	3.7

occurrence and development using readily available local climatic variables. The potential of such an index can be seen when, for each day of the 69 d field trial, a surface split index is calculated and compared to the three types of aggregated surface split length changes shown in Figure 5. That is, new surface splits occur, the existing surface splits open, and the existing surface splits close. Table 3 presents the surface split index statistics for each of the three types of surface splits. This information is graphically shown in Figure 6. This analysis suggests that new surface splits are most likely to occur when the surface split index is low, that is, less than 6. Conversely, new surface splits appear less likely to occur when the surface split index is high, that is, greater than 8.

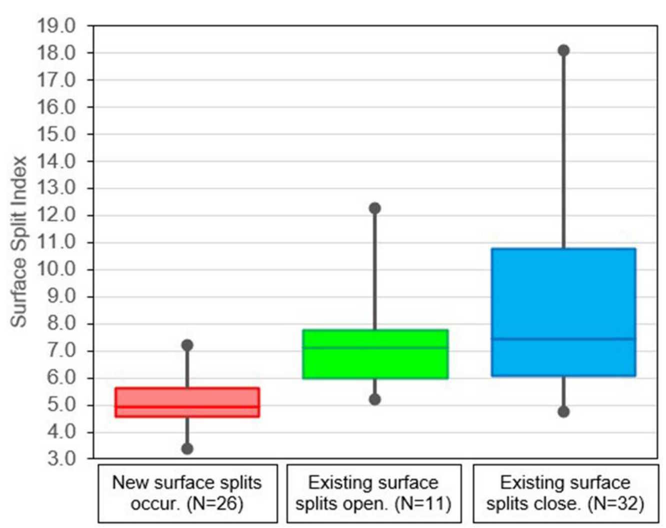

Figure 6. Surface split index (SSI) values for three types of surface splits.

3.5. Applying the surface split index (SSI) to Australian climatic conditions

Weather data was obtained for 25 weather stations in Australia from 2010 to 2021, providing 12 continuous and recent years of climate data. The criteria for selecting weather stations for analysis were Australian state or territory capital cities, as well as other major centres representative of significant and diverse Australian climatic conditions. These criteria also reflected the major population centres in Australia. The field trial site in Hervey Bay was also included. Some capital cities had numerous weather stations available, and only airport-based weather stations were selected from capital cities, given the relatively constant and open terrain at such stations. Twelve weather stations were selected from Australia and were used in this analysis. These stations are shown in Table 4 with the Köppen climate classification details (Peel *et al.* 2007). Seven Köppen climate zones are represented in this analysis with some classes, such as the more populated temperate groups, with multiple cities represented.

The proposed surface split index (SSI) algorithm summarized in Table 2 was applied to all days in the 12 year, 12 station dataset. Nominally for each weather station, there were a total of 4383 days in this period; however, in the same cases, individual climatic measurements required to calculate the SSI on a particular day were not available. The SSI for every day of an average year at a weather station was calculated by averaging the SSI for the same date across all 12 years. From this set of days, monthly SSI averages were also calculated for each of the 12 stations. In each analysis, an SSI limit of less than 6 was applied to estimate the relative daily event risk associated with the variable weather at each station. Refer to Table 5, which indicates the following. Hobart has the least number of days over 12 years, where SSI is less than six, suggesting that surface splits are relatively less likely to occur at this location. Alice Springs has the greatest number of days over 12 years, when the SSI is less than 6. All 12 months in Alice Springs were also found to have an average SSI of less than 6. This suggests extreme conditions in Alice Springs, where surface splits are more likely to occur relative to other locations. Perth, with a long dry summer, was found to have more days where SSI was less than six than the east coast state capitals. Brisbane, Sydney, and Hervey Bay, all with relatively even climate conditions throughout the year, are less likely to have periods where the SSI is less than six relative to other locations included in the analysis. Cairns was unique,

Table 4. Weather stations used in analysis and the Köppen system details.

Weather station location (city or town)	State or territory	BOM station No.	Köppen climate classification details			
			Class code	Köppen main group	Köppen seasonal precipitation type	Köppen level of heat
Cairns	Queensland	31011	Am	Tropical	Monsoon	-
Darwin	Northern Territory	14015	Aw	Tropical	Savanna, dry winter	-
Broome	Western Australia	3003	Bmh	Dry	Semi-arid steppe	Hot
Alice Springs	Northern Territory	15590	Bwh	Dry	Arid desert	Hot
Brisbane	Queensland	40842	Cfa	Temperate	No dry season	Hot summer
Hervey Bay	Queensland	40405	Cfa	Temperate	No dry season	Hot summer
Sydney	New South Wales	66037	Cfa	Temperate	No dry season	Hot summer
Hobart	Tasmania	94008	Cfb	Temperate	No dry season	Warm summer
Melbourne	Victoria	86282	Cfb	Temperate	No dry season	Warm summer
Canberra	Australian Capital Territory	70351	Cfb	Temperate	No dry season	Warm summer
Adelaide	South Australia	23034	Csa	Temperate	Dry summer	Hot summer
Perth	Western Australia	9021	Csa	Temperate	Dry summer	Hot summer

Table 5. Surface split index (SSI) analysis for 12 weather station locations.

Weather station location	Statistics for periods when SSI is < 6						Months where SSI is less than 6	Surface split hazard zone
	All 12 years (max. 4383 days)		Average year (max. 366 days)		Average months (max.12 months)			
	No. of days	%	No. of days	%	No. of months	%		
Brisbane	1399	32%	18	5%	0	0%	none	E
Hobart	1066	24%	28	8%	0	0%	none	E
Hervey Bay	1686	39%	32	9%	0	0%	none	E
Sydney	1558	36%	32	9%	0	0%	none	E
Melbourne	1477	34%	97	27%	3	25%	Dec-Feb	E
Adelaide	1614	37%	137	37%	5	42%	Nov-Mar	E
Canberra	1946	45%	138	38%	4	33%	Nov-Feb	E
Cairns	1960	45%	117	32%	4	33%	Sep-Dec	D
Perth	2635	60%	217	59%	7	58%	Oct-April	C
Darwin	3346	76%	252	69%	8	67%	Apr-Nov	B
Broome	3357	77%	312	85%	11	92%	Feb-Dec	B
Alice Springs	3833	88%	347	95%	12	100%	All year	A

Table 6. Proposed surface split hazard zones.

Proposed surface split hazard zone	Zone climatic conditions	Cities used to develop proposed hazard zones	Relative split hazard	Hazard scale (0-10)	Average daily SSI for the average year
A	Arid, hot, dry all year	Alice Springs	Extreme	9	3.0
B	Tropical, long dry winter	Broome, Darwin	Very High	8	4.7
C	Temperate, long dry summer	Perth	High	6	5.4
D	Tropical, dry early summer	Cairns	Medium	5	6.8
E	Temperate, short dry summer	Adelaide, Brisbane, Canberra, Hervey Bay, Hobart, Melbourne, Sydney	Low	4	7.6

with an early dry summer, followed by very high annual rainfall associated with monsoon conditions. Melbourne, Adelaide, and Canberra had longer drier summers than the east coast temperate locations considered.

Based on these results, cities with similar SSI statistics and/or underlying climatic conditions were grouped together. This allowed five surface split hazard zones to be suggested, reflecting the potential for surface splits to occur and develop in horizontally sheltered outdoor glued laminated timber with an equilibrated moisture content of approximately 10%. Refer Table 6. Table 6 provides a summary of the five proposed surface split hazard zones, along with the cities on which they are based, as well as an indication of the relative hazard and the proposed hazard scale. The average SSI for all days in an average year for the examined cities is also provided.

As the proposed SSI algorithm is based on 3 pm relative humidity, 3 pm temperature, and 3 pm solar radiation, it is possible to extend the proposed hazard zone system beyond the cities on which it is based by using available climate maps for

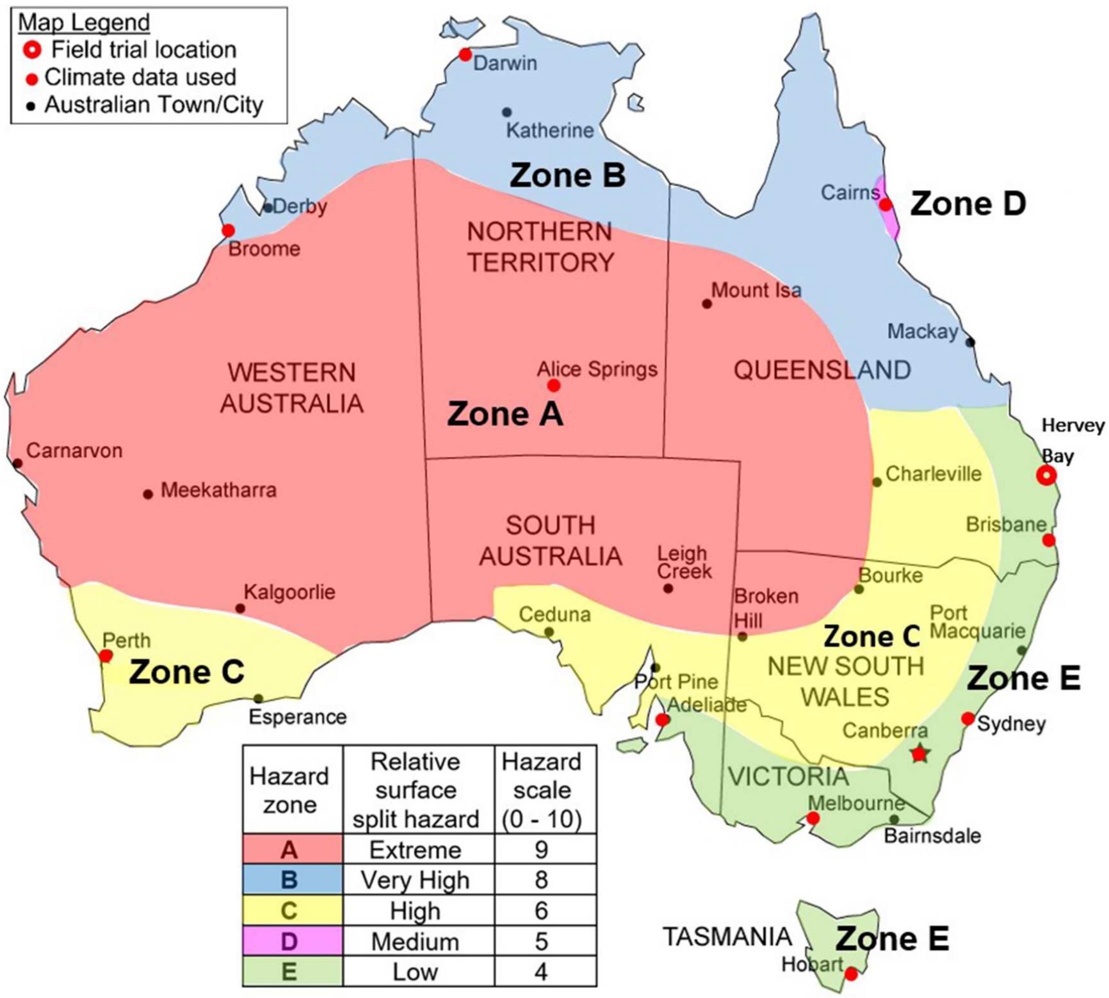

Figure 7. Proposed surface split hazard zones in Australia.

Australia. The Australian Government Bureau of Meteorology publishes maps showing isohume, isotherms, and average daily solar exposure, which are useful in establishing zone boundaries. The Köppen climate classification is also based on precipitation type and level of heat and is also useful as a guide to extend the proposed zones to other Australian regions and between the 12 selected weather stations. A proposed surface split hazard map for Australia is shown in Figure 7.

5. Discussion

The empirical approach used in this study links three environmental variables (cause) to surface splits (effect) on glued laminated timber surfaces. This approach was selected to meet the needs of practitioners, who usually only require knowledge of the main variables, a measure of the relative surface split hazard for their project location, and an appreciation of the associated uncertainties. This information allows split minimization decisions aimed at meeting structural and service life outcomes.

This empirical approach is based on many assumptions, which generally help to simplify the complexity of physics and wood science mechanisms. Therefore, the resulting hazard zone map (Figure 7), when applied to glued laminated timber structures, will have a degree of uncertainty. A mechanistic approach is desirable and would necessarily connect the intrinsic steps in the surface split process, including atmospheric heat and moisture physics, solar radiation physics, heat and mass transfer physics, the science of shrinkage strain in wood, the inherent stress – strain relationship in wood and adhesives, and the ultimate failure strength distributions in materials. A mechanistic approach is relatively complex and would also have some inherent uncertainties related to material characteristics, environmental variables, and the mechanisms selected.

An initial assumption used in this study is that daily surface split occurrence and development can be explained with the knowledge of only a few daily climatic variables, particularly relative humidity, air temperature, and solar radiation. This assumption has some validity given that relative humidity and air temperature are known to influence the moisture content of wood (Simpson 1973), which in turn can lead to shrinkage strain, tension stress, and surface splits. The assumption that solar radiation may also have a direct influence on timber surfaces has some basis (Castenmiller 2004), with cracking of window frame joints when solar radiation causes high temperatures. The SSI algorithm also assumes that solar radiation induced wood temperature can simply be added to air temperature times a calibration factor to calculate the SSI. This is a simplification from a mechanistic viewpoint, but it is justified by the relationship between the SSI and the surface split type, as shown in Table 3 and Figure 6.

Another assumption made in this analysis is that a single 69 d trial with only 18 laminates and 16 gluelines in four beams at a single Australian site can be used to propose a hazard map for all Australian conditions. While this appears implausible, the climatic variation within a single day and between the 69 days in this trial period represents a range of daily climatic conditions typically experienced in many other Australian climates. The 69 daily climates in the field trial varied from hot dry sunny days to cooler, wetter, and overcast days. An examination of the average daily relative humidity range provides some evidence that Hervey Bay is representative of other Australian climates. During the field trial the maximum daily change in relative humidity (54%) was from 95% to 41% on the 28/1/23, while the minimum daily change in relative humidity (9%) occurred on the 17/1/23. The average daily change in relative humidity for the full 69 d trial in Hervey Bay was 34%, corresponding to the generally higher humidities at this time of year. Over the 12 year climate period used elsewhere in this study, the average daily change in relative humidity for Hervey Bay was 41%. The average daily change in relative humidity for Alice Springs, Hobart, and Perth over the same 12 years from 2010 to 2021 was 43%, 41% and 49%, respectively. Although atmospheric moisture levels may vary across Australia, the average daily change in relative humidity is quite similar for places like Hervey Bay, Hobart, Perth, and Alice Springs. It is this change in relative humidity which is a key flux for moisture content changes in timber. The daily change in climate at the trial site over the 69 d period, reflected in the relative humidity measurements, is representative of the average daily relative humidity change in other Australian climates. The most significant extrapolation of the trial data would be the application of the SSI model and hazard map to extreme climates within Australia.

The use of the proposed hazard map by practitioners for other species and other adhesives also requires the assumption that the occurrence and development of surface splits in the hybrid plantation pine species and PUR adhesive used in the trial is relative to surface split occurrence and development in other timber species and adhesives. The species used in this trial resulted in a quick and measurable surface split response, which facilitated sufficient results to discern key climatic influences and develop a hazard map. Other species with different diffusion, shrinkage, strain, and stress characteristics, and adhesives with different characteristics may not behave in a way that is relative to the pine species and PUR adhesive used in this trial.

The application of the proposed hazard map to glued laminated timber with different initial moisture conditions is also uncertain because this study is based on timber with an initial moisture content (10%) equilibrated to service conditions. Where the initial moisture content of timber has an average and/or variation above or below an equilibrated moisture content, then surface splits may vary from this trial. For instance, if timber with an average moisture content of 15% is used, the shrinkage strain could be more significant in outdoor climates with an EMC less than this, resulting in increased stress and potentially an increase in surface splits. In an extreme case, the use of very high moisture content wood in a location such as Alice Springs would be expected to result in considerable surface splits. Conversely, timber with very low moisture content used in a climate with a higher EMC may show fewer surface splits. The moisture content of the glued laminated timber in the trial was well-suited to the trial site conditions. It is a general prerequisite that seasoned timber products should have a moisture content that suits the service environment.

Modelling the potential surface split hazard in 12 cities using 12 years of daily climate data and then grouping these (Table 5) into SSI zones with potentially similar surface split hazards generates some uncertainty. While Zones A, B, C, and D are straightforward, the grouping of the more populated cities within Zone E brings some uncertainty. Zone E is where glued laminated timber structures are more likely in Australia. There are clear differences between the climates of the seven cities in Zone E. Hervey Bay, Brisbane, Sydney, and Hobart with relatively "even" climatic conditions are different from those of Melbourne, Adelaide, and Canberra, which all have pronounced dry summers. Adelaide and Canberra are both near the Zone C boundary. Surface split hazards in the summer months in Adelaide, Canberra, and Melbourne warrant further study and a precautionary approach. The drafting of hazard zone boundaries between cities also has some uncertainties. The proposed boundaries are based on general regional climate information, which reflects the known relative humidity and air temperature distributions.

The proposed SSI algorithm in Table 2 assumes that the influence of solar radiation on surface splits is simply related to an increase in temperature; however, this may not be the case. Although direct solar radiation acting on a material can cause temperature increases, the ultraviolet (UV) component of the solar spectrum is known to cause deterioration in wood (Volkmer 2013). This UV break down of wood at the surface may be causing micro fractures which then propagate into the larger surface splits observed in this study. The calibration factor (2.93) applied to the combined surface temperature seems larger than expected and may suggest another mechanism, beyond the influence of temperature on vapour diffusion.

The grouping of cities into hazard zones (Table 5) was based on an analysis of SSI less than six over different time periods: 12 years, one year and 12 months. Climatic conditions over time and an average analysis may not fully reflect more volatile conditions conducive to surface splits. The SSI variation between the 4300 + days in each city is worth considering. Perhaps a city with relatively less SSI variation may not have the same number of surface split events as a city with relatively more SSI variation. Table 7 summarizes the variation statistics for each of the 12 cities over the 12 years, with a ranking by coefficient of variation. Standard deviation values assume that SSI distributions are normal; however, they are generally positively skewed owing to the high SSI values associated with rain events. This variation analysis generally shows that a lower SSI variation corresponds to a hazard zone. Cairns is an exception, with a relatively low SSI variation, and yet is fifth in order after Zones A, B, and C.

Table 7. Surface split index (SSI) variation statistics.

Hazard zone	City	Days in 12 years (No.)	SSI 12 year average	SSI variation statistics		
				Standard deviation	Range	Coefficient of variation (%)
E	Hobart	4373	8.28	3.51	25.2	42.4%
D	Cairns	4367	6.77	2.91	22.9	43.0%
E	Brisbane	4374	7.41	3.20	24.4	43.2%
E	Hervey Bay	4327	7.53	3.68	24.5	48.9%
E	Sydney	4332	7.85	4.05	27.7	51.6%
E	Adelaide	4374	7.38	3.93	25.6	53.2%
E	Melbourne	4366	7.80	4.19	26.2	53.7%
E	Canberra	4367	7.01	4.39	28.3	62.7%
C	Perth	4364	5.38	3.71	26.0	68.8%
B	Broome	4373	4.36	3.02	26.6	69.3%
B	Darwin	4377	4.96	3.48	22.8	70.0%
A	Alice Springs	4372	3.05	3.45	26.3	113.0%

The use of a surface split hazard map alone simply provides an indication of the relative surface split hazard faced by unfinished glued laminated timber used in an outdoor undercover climate in Australia. Improving surface performance requires linking the relative split hazard to appropriate design, construction, and/or maintenance actions, which will minimize surface split occurrence and development. Split minimization or control actions may involve a range of activities, either in isolation or in combination. An action corresponding to a particular split hazard zone may involve the selection of timbers with high perpendicular to grain strength, selection of timbers with inherently low shrinkage characteristics, selection of timbers with low moisture vapour diffusion coefficients, application and maintenance of surface finishes which limit moisture vapour diffusion and/or strengthen the surface, use of solar shielding devices and/or surface orientation to reduce solar radiation, glued laminated timber manufacturing specifications, wood modification processes to minimize surface split occurrence, an in-service inspection regime that detects early signs of surface splits, and maintenance activities which act on any detected deterioration to minimize further splits. etc. Performance trials, manufacturer claims, and/or engineering judgement may also provide the basis for appropriate action.

The analysis focused on surface splits in the laminates only, and not on surface splits at or near the gluelines. As a result, the findings are potentially applicable to wood surfaces in general, and not just to glued laminated timber surfaces.

There are similarities between the proposed surface split hazard map and the Köppen climate classification system (Peel *et al.* 2007) for Australia. This is not unexpected, as this classification system is based on precipitation type and level of heat, the same climatic variables underpinning the occurrence and development of surface splits. A potential future correlation between the Köppen climate classification system and the proposed surface split index may facilitate the use of this international system as a guide to surface split hazards across the globe. Such a correlation would require appropriate field trial evidence.

Additional field trials would help calibrate the proposed model and better quantify surface split minimization actions. Subsequent trials may include investigations of different climate locations, timber species, adhesives, initial moisture contents, and surface finishes/treatments. The proposed surface split index and the resulting hazard map could also be refined with additional field trials.

6. Conclusions

Based on the field trial reported and the empirical analysis used to develop a proposed hazard map for surface splits in outdoor undercover glued-laminated timber not exposed to precipitation, the following conclusions were made:

1. Air temperature, relative humidity and solar radiation are primary causes of surface splits.,
2. The afternoon alignment of the maximum air temperature, minimum relative humidity, and maximum solar radiation can create shrinkage strain and perpendicular to grain stress, which is conducive to the occurrence and development of surface splits.,
3. An empirical model using 3 pm measurements of temperature and relative humidity, and a calculated 3 pm solar radiation value, provides a basis for a surface split index (SSI), and identifies conditions that correlate to surface split occurrence.,
4. Daily climatic conditions with a calculated SSI of less than 6 were associated with the occurrence of new surface splits, whereas days with an SSI greater than 6 corresponded to the opening or closing of existing surface splits.,
5. The proposed five-zone surface split hazard map (Figure 7) has the potential to assist structure owners, designers, builders, and maintenance professionals to better estimate relative in-service surface integrity issues in exposed glued laminated timber., (Caution is recommended in any application of the hazard map, given the limited field evidence on which it is based.)
6. The main uncertainties affecting the reliability of the proposed hazard zone map (Figure 7) are the initial moisture content of the glued laminated timber relative to the in-service EMC of a location, timber species other than *pinus* species, adhesives other than PUR adhesive, and Australian climates that are extremely different from the trial site.

Author contributions

CRediT: **Geoffrey Stringer:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Writing – original draft, Writing – review & editing; **Dilum Ferando:** Supervision; **Chandan Kumar:** Supervision; **Michael Heitzmann:** Supervision.

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