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TIMBER CLADDING DISCOLOURATION IN TROPICAL MONSOON CLIMATES

Shinya Okuda[1], Laurent Corpataux[2], Kua Harn Wei[3]

ABSTRACT: This paper addresses the factors affecting timber facade discolouration in tropical monsoon climates. We measure the colour change of timber cladding in the northern (N), eastern (E), southern (S) and western (W) orientations in relation to the prevailing wind directions through a year-long field test. The objective is to find a way to guide the timber cladding discolouration in a more controlled manner. The background aim of this research is to reduce the existing negative preconception of timber resulting from the visual discomfort of uneven timber colour change, which contrasts with the established industrial aesthetic norms. The following tectonic configurations were tested: i. Red balau (*Shorea collina*) timber cladding in horizontal and vertical orientations and ii. Norway spruce (*Picea abies*) and red jabon (*Anthocephalus macrophyllus*) cross-laminated timber walls overlayed with ultraviolet-filtered glazing. The discolouration was measured using a Konica Minolta handheld spectrophotometer CM-2600d, and the results were assessed in the colour space of CIE $L^* a^* b^*$. The average discolouration (ΔE^*) was the largest in the S- and W-side vertically oriented boards ($\Delta E^* = 17.0\text{-}18.4$) and the smallest in the N-side horizontally orientated boards ($\Delta E^* = 10.2$). The horizontally oriented boards exhibited lower and more uneven discolouration than the vertically oriented boards. The prevailing S and SSW wind direction on-site may have concentrated the driving rainwater on the S and W facades, resulting in faster and more even colour changes on the vertical boards.

KEYWORDS: Timber cladding; colour change; monsoon wind; weathering; tropics

1 INTRODUCTION

1.1 TIMBER AS INDUSTRIAL MATERIAL

While wood was the most prevalent building material before the nineteenth century, since the Industrial Revolution, we have relied on steel and concrete as the major building materials for the construction of our cities [1]. Wood's decline was furthered by the emergence of modern architectural styles that promoted the use of mass-produced industrialised components, often to achieve a universal aesthetic. Wood, with its ever-changing appearance resulting from chemical and physical degradation, was deemed unsuitable in the era of industrialisation.

The recent development of new composite wood products and timber construction technologies, along with amendments to building codes, has allowed timber construction to finally resurge in the late twentieth century [1].

Most buildings today are erected using hybrid construction techniques that utilise a combination of different materials for technical, functional or aesthetic reasons. When building with wood, non-combustible elements made of steel or concrete are frequently incorporated to enhance characteristics such as structural capacity, fire resistance and acoustic performance.

As a natural material, various properties of wood continue to change even after it has been harvested, sawn, dried, converted into building products and incorporated into structures. UV radiation gradually affect exposed wood, and the associated visible degradation of surfaces can be polemic topic. While some cultures may accept and appreciate the look of weathered and worn wood, it is not always the case when more permanent industrial aesthetics is preferred. The use of timber as a building material is increasing in urban environments, where the majority is made of industrial materials, such as concrete and steel, finding ways to incorporate ephemeral timber aesthetics with the established norm of industrial aesthetics is important and influence to the popularity of timber construction in the future [1].

1.2 PUBLIC PERCEPTION OF MASS-ENGINEERED TIMBER IN SINGAPORE

In Singapore, the Building & Construction Authority (BCA) is pushing the use of mass-engineered timber (MET) due to the increasing need for smarter, greener and higher-quality building structures. This positions MET as a valuable solution for heightened productivity and sustainability in construction. According to a survey by Low et al. [2], professionals in the Singapore construction industry recognise MET's normative and rational merits, including the enhancement of biophilic aesthetics, a decreased carbon footprint, shorter construction time and the reduction of on-site waste. However, cultural and cognitive barriers have been identified as the key factors preventing the adoption of MET in Singapore, including a lack of knowledge and expertise in MET, a shortage of commercial opportunity and challenging raw material acquisitions from overseas, in addition to the higher costs associated with importing MET. These challenges have resulted in the limited adoption of this technology, and few projects in Singapore using MET have been constructed to date. Interestingly, the 'enhanced beauty of buildings' is listed

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[1] Shinya Okuda, National University of Singapore, Singapore, akiso@nus.edu.sg

[2] Laurent Corpataux, laurent1corpataux@gmail.com

[3] Kua Harn Wei, National University of Singapore, Singapore, bdgkuahw@nus.edu.sg

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among the top drivers of MET adoption, which implies greater concern for the visual quality of MET projects. Therefore, understanding the key factors that cause changes in the colour of timber in tropical monsoon climates and ways to predict it in a controlled manner may help to promote the long-term adaptation of MET buildings in Singapore.

2 LITERATURE REVIEW

2.1 TIMBER DISCOLOURATION

Biodegradation, weathering and ageing can deteriorate wood as a natural material [3]. Wood discolouration is a complex phenomenon, mainly affected by heat, light, physiological and biochemical reactions and microorganism attacks [4].

The colour change manifests in a range from a reddish yellow to a dark brown tone depending on the intensity and duration of the radiation. The red tones in wood are often attributed to extractives within the wood, while the yellow tones are mainly dictated by the photochemistry of the wood, especially in relation to lignin [4].

2.1.1 Weathering

Hill et al. [5] explain that weathering is a combination of biotic and abiotic degradation mechanisms acting on the wood's surface. Prolonged exposure to ultraviolet (UV) light degrades the lignin in wood, which is an organic polymer responsible for binding the cellulose fibres together. The decomposed lignin is soluble in water and may therefore be dissolved and washed out by driving rain, leaving behind the white cellulose fibres [1].

The degradation of lignin produces fragments that act as nutrients for mould and fungi, leading to increased crack formations in the exposed wood. As weathering progresses, the bleached surface region of the wood develops a grey colour as the wood is colonised by mould and staining fungi (e.g., *Aureobasidium pullulans* and *Sclerophoma pithyophila*).

The length of time that the wood is wet is a significant factor in determining the likelihood that mould or stains will develop, and surfaces that dry rapidly because of prevailing winds are much less likely to show mould growth [5]. The completely weathered grey layer is only a few tenths of a millimetre thick, and, within two millimetres from the surface, the wood itself is not affected any further. The effect of weathering on strength properties is very limited [6].

2.1.2 Ageing

Matsuo et al. [3] explain that ageing proceeds slowly in wood through a combination of omnipresent oxygen and water. The ageing and subsequent change in wood colour begin at the time of tree harvesting. Colour properties are in direct relation to ageing (the lightness of the wood decreases, and the hue becomes slightly redder). The colour change during natural ageing could be explained as a mild thermal oxidation process. In other words, heat treatment could accelerate the wood's change in colour that occurs during ageing.

It is generally accepted that colour changes increase as the temperature increases. Heat can directly alter the colour by causing hydrolysis and the oxidation of the wood's components. As timber dries, extractives accumulate on the surface and oxidise, manifesting as a brown colour. According to White and Dietenberger [4], the darkening of wood due to heat is caused by the thermal degradation of hemicelluloses and lignin. Tolvaj et al. [7] studied the effects of steam on softwood's change in colour, which showed a slow but continuous increase in redness at 70°C and a linear correlation between lightness and colour hue at all steaming times and temperatures.

3 RESEARCH METHODOLOGY

The National University of Singapore (NUS) and City Developments Limited's (CDL) Tropical Technology (T^2) lab (Figure 1) was set up at the end of 2018 at NUS in Singapore to investigate the influence of aspects of tropical climates, such as sun, wind and humidity, on photovoltaic panels, green façades and natural ventilation and the behaviour of MET under tropical climate conditions. The MET façade field test was conducted for one year, from January to December 2019, at the T^2 lab, which was naturally ventilated with no casting shadows from the surroundings throughout the testing period.

Figure 1: *Tropical MET architectonics study set up at NUS-CDL T^2 Lab (Nov. 2018)*

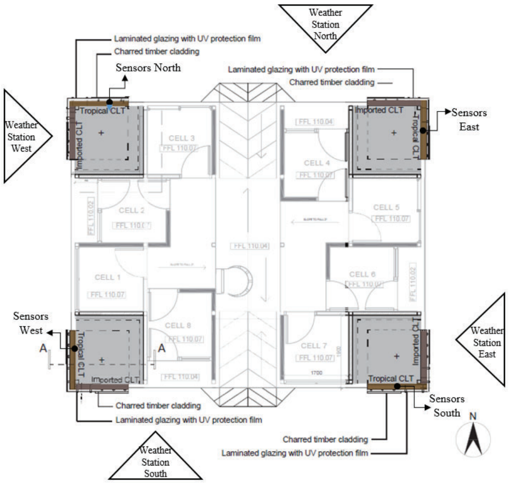

Figure 2: *The locations of the sensors and weather stations*

3.1 FIELD TEST

The four facades of the NUS-CDL T^2 lab are perfectly aligned to the north, east, south and west (N, E, S and W) orientations (Figure 2). The four test corners consisted of

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NUS custom-made tropical cross-laminated timber (CLT) walls made of red jabon (*Anthocephalus macrophyllus*), a fast-growing tropical plant [8], in a side-by-side comparison with Norway spruce *(Picea abies)* CLT imported from Europe, which has been the local standard since 2012 due to Singapore's Eurocode compliance. Each CLT panel was 2.4 m in height and 1.4 m in width with 150 mm thickness and was clad with three façade configurations: horizontally (H) and vertically (V) oriented red balau (*Shorea collina*) timber cladding and UV-filtered grazing (Figure 3).

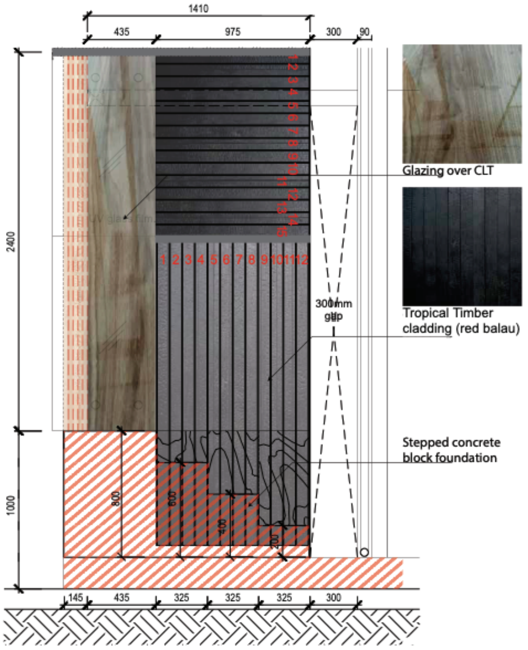

Figure 3: *An illustration of the typical CLT wall configuration at the* T^2 *lab.*

3.2 THE SELECTION OF TIMBER SPECIES FOR CLADDING

Untreated red balau (*Shorea collina*) was selected for timber cladding tests, which is classified as moderately durable for fungal and termite attacks according to BS EN350:2016. Red balau is also commonly used for outdoor decking and cladding in Singapore.

3.3 CIE-L*a*b* ANALYSES

In accordance with BS EN ISO 11664-4:2011, the change of colour coordinates (ΔL^*, Δa^* and Δb^*) were calculated as the difference between the value of the control samples and the value of the tested specimen. We measured the average of two control samples for 200 timber boards across the four orientations.

The measurements were recorded using a Spectrophotometer CM-2600d (Konica Minolta), which was set to measure the samples' L*, a* and b*colour coordinates, where L* is lightness from 0 (black) to 100 (white), a* is chromaticity coordinate + (red) or − (green), and b* is chromaticity coordinate + (yellow) or − (blue). From the relative colour changes, ΔL^*, Δa^* and Δb^* (i.e. changes between the weathered and control samples), the total colour difference, ΔE^*, was calculated by equation (1) [9] to compare the individual colour shades.

$$\Delta E * = \sqrt{\Delta L * 2 + \Delta a * 2 + \Delta b * 2} \tag{1}$$

There were noticeable natural colour differences among the timber specimens at the beginning of the tests (Figure 4, left). To minimise the influence of the natural colour variations, each board was measured at three points (left, middle and right for the H-oriented boards and top, middle and bottom for the V-oriented boards) to determine the average ΔE^* for each timber board (Figure 4 Right).

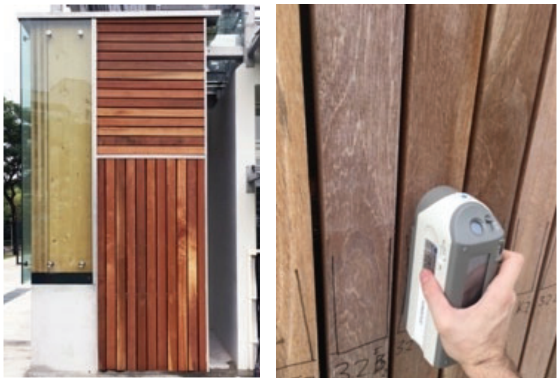

Figure 4 Left: *Newly installed tropical timber cladding (red balau). There were noticeable natural colour differences among the timber boards. (W side, Oct. 2018)* ***Right:*** *Colour measurement with handheld spectrophotometer (Konica Minolta CM-2600d). Each board was measured at three points to determine the average* ΔE^* *for each timber board.*

3.4 UV-FILTERED GLAZING

Cross-laminated timber is only to be used for service classes 1 and 2 (BS EN 1995-1-1:2004+A2:2014), which means it is not possible to use it for service class 3: direct exposure to the weather (NA to SS EN 1995-1-1:2018). The UV-filtered glazing overlaying CLT walls could be considered as service class 2, which makes untreated timber visible through the glazing (Figure 4, left).

To effectively cut the UV exposure, 3M Prestige Window Film PR70 (Visible light transmitted: 69%/UV rejected: 99.9%/Infrared rejected: 97%/Total solar energy rejected: 50%) was applied inside the glazing. A point-fixing method was used to fix the glazing on both the NUS custom-made tropical CLT and the spruce CLT.

Wong et al. [10] simulated the surface temperature profile of a double-glazed wall in the context of Singapore. The external surface temperature of a double-glazed facade could become very high if heat absorption glass is used. But the mechanism of heat extraction, either by stack effect or mechanical fans, in the double-glazed cavity can maintain a lower internal surface temperature, thus minimising solar heat transfer to the internal spaces. As in the case of the fourth-floor east orientation, with the external surface of the inner layer glazed wall with no ventilation as the worst scenario, the most probable temperature is around 37–38°C. To generate sufficient natural ventilation by stack effect in the façade cavity, we kept the bottom part and the vertical gaps between the two glazing panels open.

4 RESULT AND DISCUSSION

4.1 LEACHING EXTRACTIVES

Figure 5: *Brown stains on the concrete foundation were observed during the first few months after the installation. They were likely deposited by leached extractives from the red balau timber (red dotted circle, October 2018)*

The installation of timber cladding specimens was completed in October 2018. Temporary brown stains on the concrete foundation were observed for the first few months, which were likely deposited by leached extractives from the red balau façade. Those stains were later washed away by natural rainfall.

For the first two months between October and December 2018, the rapid discolouration (ΔE*) between the averages of the two control samples and the 200 specimens was recorded (ΔE* = 6.5–8.7, Figure 5, 7). There were noticeable natural colour differences among the 200 specimens initially (Figure 4, left), which might make the difference in the colour change (ΔE*) in the orientations less clear. After two months' exposure, the natural variations in colour among the specimens seemed to be relatively moderate. Therefore, we excluded those first two months (ΔE*) in the colour change analysis (Figure 7).

4.2 COLOUR DIFFERENCES IN ORIENTATION

The average colour coordinate of the two controlled samples was recorded as (L*: 48.24, a*:11.58, b*: 19.50) prior to the testing. The colour measurement of the 200 specimens in the NWSE orientations was recorded at two-month intervals between December 2018 and December 2019 for one year. The colour change field test result is shown in Figure 7.

The decrease in the lightness of the specimens was recorded for all samples. After the testing period, the overall colour change, Δ*E**, was the largest in the S- and W-side V-aligned cladding (Δ*E** = 17.0–18.4), which was classified as a different colour according to the colour change assessment guidelines (Figure 6). The smallest Δ*E** was the N-side H-aligned cladding (Δ*E** = 10.2), which was classified as a distinct colour change according to the same assessment guidelines.

ΔE^*	Description
$\Delta E^* < 0.2$	Invisible changes
$0.2 < \Delta E^* < 2$	Small changes
$2 < \Delta E^* < 3$	Colour changes visible by high quality filter
$3 < \Delta E^* < 6$	Colour changes visible by medium quality filter
$6 < \Delta E^* < 12$	Distinct colour changes
$\Delta E^* > 12$	A different colour

Figure 6: *Assessment guidelines for colour change* [11]

It is generally observed that the overall colour change (ΔE*) on the S and W sides increased faster than on the E and N sides, except for the E-side V-aligned boards, where the ΔE* increased as fast as the S and W sides. The colour change (ΔE*) differences in orientations generally grew wider over the testing period (Figure 7).

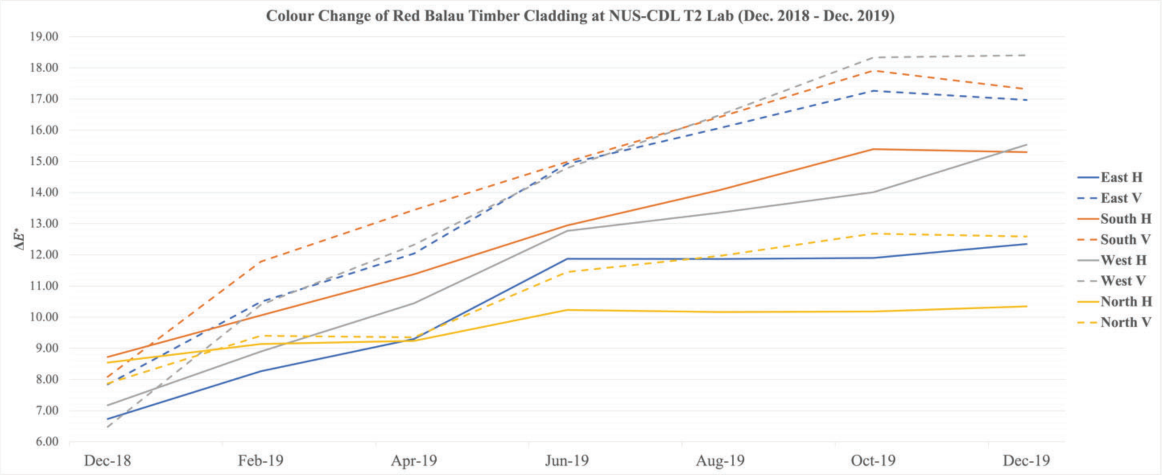

Figure 7: *Discolouration of the red balau V- and H-aligned cladding in NWSE orientations.*

4.3 HORIZONTAL/VERTICAL CLADDING

It was observed that the H-aligned boards exhibited lower overall discolouration (ΔE*) values than the V-aligned boards. Except for the first measurement in December 2018, when the initial natural colour variations among the specimens were still prevalent, all the other measurements exhibited lower ΔE* in the H-aligned boards than the V-aligned boards. Generally, the gaps in ΔE* between the H- and V-aligned boards continuously increased, except for the last measurement in December 2019 (Table 1).

Table 1: *The discolouration (ΔE*) comparison between H and V-aligned red balau timber cladding in the NWSE orientations. Except for the first measurement in December 2018, all other measurements exhibited higher ΔE* for the V-aligned boards than the H-aligned boards (Ref. red underlined figures).*

	Control Samples	**ΔE***						
	(Oct-18)	**Dec-18**	**Feb-19**	**Apr-19**	**Jun-19**	**Aug-19**	**Oct-19**	**Dec-19**
East Horizontal (H)	0.00	6.73	8.26	9.30	11.87	11.86	11.90	12.34
East Vertical (V)	0.00	7.84	10.49	12.04	14.92	16.07	17.26	16.97
East V-H	0.00	1.11	2.23	2.74	3.05	4.21	5.36	4.62
South H	0.00	8.72	10.06	11.38	12.94	14.08	15.39	15.30
South V	0.00	8.08	11.78	13.44	14.99	16.43	17.91	17.32
South V-H	0.00	-0.64	1.72	2.06	2.04	2.35	2.52	2.02
West H	0.00	7.17	8.89	10.45	12.77	13.35	14.01	15.53
West V	0.00	6.48	10.40	12.32	14.79	16.49	18.33	18.40
West V-H	0.00	-0.70	1.50	1.87	2.02	3.14	4.32	2.87
North H	0.00	8.54	9.14	9.24	10.23	10.16	10.18	10.35
North V	0.00	7.87	9.40	9.35	11.45	11.97	12.68	12.59
North V-H	0.00	-0.67	0.27	0.12	1.22	1.80	2.50	2.24

Figure 8: *ΔE∗ standard deviation among all H-aligned and V-aligned boards in each orientation (**Upper Left:** E, **Upper Right:** S, **Lower Left:** W, **Lower Right:** N.)*

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Figure 9: *An example of cladding at the SW corner (facing S) a few hours after heavy monsoon driving rain (Nov. 2019). The H-aligned cladding was mostly still wet, while the V-aligned cladding dehydrated relatively quickly.*

The ΔE* standard deviation among all H- and V-aligned boards in each orientation was computed to understand the degree of even discolouration. While it was generally observed that the discolouration (ΔE*) standard deviation became smaller in the S orientation, there were two exceptions: the E-side V-aligned boards at the beginning of the testing period and the W-side H-aligned boards in October 2019.

The former was due to the initial natural colour variations among the specimens, as the ΔE* standard deviation for the V-aligned boards in all orientations stabilised after six months.

The latter helps us to understand the cause of the late ΔE* standard deviation spike in the H-aligned boards, which fluctuated more than the V-aligned boards throughout the testing period. As UV-degraded lignin is washed away by rainwater, the fluctuated discolouration (ΔE*) standard deviation might be caused by water-flow patterns over the H- and V-aligned boards.

Figure 9 illustrates an example of the S facade a few hours after the heavy monsoon driving rain. While the H-aligned boards retained their wet surfaces for a longer period, the V-aligned boards exhibited a relatively quicker drying process, which implies that the driving rain ran smoothly along the direction of the wood grains. In contrast, the water flow direction was not aligned with the direction of the wood grains in the H-aligned boards, resulting in wet surfaces for relatively prolonged periods.

4.4 MONSOON WIND AND RAIN SHOWERS IN THE TROPICS

In the tropical monsoon climate, much of the rain is heavy and accompanied by monsoon wind. Timber weathering is caused by UV decomposing the lignin, which is soluble in water and may therefore be dissolved and washed out by driving rain [1]. Therefore, the prevailing wind direction is an important factor influencing timber weathering in the tropical monsoon climate.

Two monsoon seasons and two inter-monsoon periods define Singapore's local climate. The two monsoon seasons are the southwest monsoon season (June to September, south-easterly to southerly winds) and the northeast monsoon season (December to early March, northerly to north-easterly winds), while the two inter-monsoon periods take place from late March to May and from October to November with light breezes. Rainfall is plentiful in Singapore, with an average of 167 rainy days per year. The long-term mean annual rainfall from 1981 to 2010 was 2165.9 mm [12], which is approximately three times higher than the mean annual precipitation in Germany from 1991 to 2020 (728.9 mm) [13], for example.

According to the annual wind rose for 1981–2010 in Singapore [12], the two prevailing wind directions are NNE and S. However, the Figure 7 discolouration analysis indicated that the highest discolouration occurred in the S and W orientations, while the N orientation recorded the lowest level of discolouration.

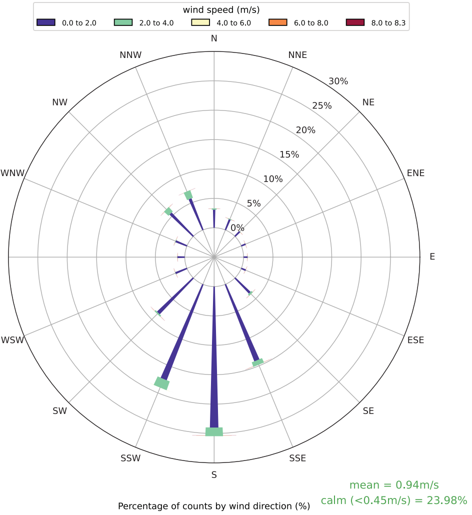

Figure 10: *Annual wind rose based on the measurement at the NUS-CDL T2 lab, January to December 2019*

We further analysed the wind data recorded at the rooftop level of the NUS-CDL T^2 lab. The 2019 annual wind rose at the T^2 lab (Figure 10) indicates the clear S and SSW dominant wind directions, which deviate from the prevailing monsoon wind direction. Therefore, the higher and faster discolouration in the S and W orientations might be a result of heavy monsoon driving rain by the locally dominant S and SSW wind at the T^2 lab site.

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However, we are not certain of the cause of the deviated dominant wind direction at the T^2 lab site. The T^2 lab site was surrounded by high-rise residential buildings, which are typical in Singapore's high-density urban environment. This might be the cause of the varied wind directions at the rooftop level of the low-rise T^2 lab. This may indicate that local wind measurements are important for estimating the weathering effects in Singapore's high-density urban environment.

4.5 RAIN SPLASH WATER

The growth of decay-producing fungi only occurs if wood is continuously saturated with water in the presence of oxygen and its moisture content remains above 20% over prolonged periods. Construction details that either keep building components dry or help them to dry quickly will reduce the likelihood of infestation by wood-destroying fungi and insects. Best practices include raising wooden facades high enough above adjacent horizontal surfaces to prevent damage caused by splashing water [1].

According to the DIN 68800, the distance between the underside of exposed timber members or construction elements and the ground (or surrounding surface) must be at least 30 cm to prevent exposure to splash water. This distance can be reduced to 15 cm if additional technical measures, such as a gravel bed in front of the timber cladding, are taken to reduce the impact of splashing [14].

The greying of damp wood is generally due to the presence of stain fungi (*Aureobasidium pullulans*). The hyphae of these fungi are pigmented, and they tend to refract visible light; accordingly, the timber surface appears grey. Refraction varies depending on the surface moisture content, and weathered timber is always darkest when wet [15].

At the NUS-CDL T^2 lab, where there is no shade from the surroundings, generally strong splashes at the ground level were observed when tropical monsoon driving rain directly hit the concrete ground surface. We intentionally narrowed the gaps between the bottom end of the timber cladding to the ground level to 20 cm to observe how high the splash water could wet the timber façade with the tropical monsoon driving rain.

Figure 11 illustrates an example of timber cladding on the S side several hours after heavy monsoon driving rainfall. Generally, we observed that the wall base became wet and darker up to 40 cm in height in the S and W orientations. The tendency was less obvious in the N and E façades. If we were not mitigating the splash water through additional technical measures, it would probably have been better to raise the bottom end of the timber cladding at least 40 cm from the ground level to protect the timber façade from constant wetting, especially for the façade facing prevailing wind directions in the tropical monsoon climate.

Further investigation is needed to develop guidelines; however, the 30 cm guideline in the temperate climate is not sufficient in the tropical monsoon climate.

Figure 11: *An example of a wet timber cladding base several hours after heavy monsoon driving rainfall (November 2019) – generally, the bottom of the S and W façades became wet and grew darker because of the splash water up to 400 mm above ground level.*

4.6 UV-FILTERED GLAZING

The UV-filtered glazing overlayed CLT walls made of Norway spruce (*Picea abies*) and red jabon (*Anthocephalus macrophyllus*) to protect them from weathering and make them visible from the outside.

As the UV-filtered glazing was point-fixed over the CLT walls, the colour change measurement via handheld spectrometer was restricted. Instead, the general discolouration observation was made visually after 28 months of exposure as a reference.

Figure 12: *Examples of colour changes after 28 months exposure behind UV-filtered glazing (April 2021).* ***Left:*** *Norway spruce (Picea abies),* ***Right:*** *Red jabon (Anthocephalus macrophyllus).*

As the UV-filtered glazing effectively protected the CLT walls from monsoon driving rain, there were no signs of grey colour weathering observed for both the Norway spruce and red jabon. However, noticeable colour changes were still observed, especially for the Norway spruce, which changed to a darker reddish colour over time, while the red jabon's change in colour was less obvious. There were also noticeable cracks on both the Norway spruce and red jabon CLT walls (Figure 12).

The visually noticeable dark reddish colour changes of the Norway spruce and the moderate reddish colour of

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the red jabon seemed to be a part of the ageing process, which is considered as a slow thermal oxidation [3]. It is generally observed that heat can directly alter the colour by causing hydrolysis and the oxidation of wood components. As timber dries, extractives accumulate on the surface, where they oxidise to a brown colour. The effect is usually short-lived, as rainwater will remove the extractives, although it can persist where the timber is protected [15]. It is also generally accepted that colour changes increase as the temperature increases. Long-term exposure to heated double facade cavities in hot and humid climates probably accelerates the ageing process. This phenomenon requires further investigation.

Figure 13 *Examples of overall timber cladding discolouration after 28 months exposure (April 2021).* ***Left:*** *N side,* ***Right:*** *S side. The S-side facade exhibits mostly darker colours, while the N-side facade exhibits more moderate and uneven colour changes.*

5 CONCLUSIONS

Timber weathering is caused by UV decomposing the lignin, which is washed out by the driving rain. In tropical monsoon climates, much of the rainfall is heavy and accompanied by monsoon wind. The mean annual rainfall in Singapore is approximately three times higher than in Germany. Therefore, the prevailing wind direction is one of the important factors influencing timber weathering and discolouration in tropical monsoon climates.

The overall colour change (ΔE^*) was the largest in the S- and W-side V-aligned cladding ($\Delta E^* = 17.0–18.4$), and the smallest ΔE^* was the N-side H-aligned cladding ($\Delta E^* = 10.2$). The dominant wind directions at the T^2 lab were S and SSW; therefore, monsoon driving rain seems to be the main cause. However, in Singapore's high-density urban environment, the prevailing wind direction in microclimates may differ from the prevailing monsoon wind direction. Therefore, on-site wind measurement is essential to estimating future weathering.

The general observation was made that the H-aligned boards exhibited lower overall discolouration (ΔE^*) than the V-aligned boards. The ΔE^* standard deviation for the H-aligned boards was generally higher than the V-aligned boards throughout the testing period. After a 28-month period, the V-aligned boards exhibited a relatively homogeneous facade outlook, while the H-aligned boards still exhibited uneven weathering (Figure 13). Despite the UV-filtered glazing, the natural colour changes still occurred for the CLT walls, which seemed to be caused by a mild thermal oxidation process. The effect of prolonged exposure to the heated double-grazing cavity requires further investigation.

The discolouration of timber elements is unavoidable; however, if the discolouration could manifest more evenly, it could still resonate with the dominating industrial aesthetics. The field test demonstrated that vertical cladding constantly exhibited a lower ΔE^* standard deviation than horizontal cladding, which means that relatively even weathering can be expected. Overall, this is still an initial attempt to control the discolouration of timber facades in tropical monsoon climates. We must investigate with further variations in tectonics and more tactile strategies to control and blend in ephemeral timber aesthetics with the industrial aesthetic norms. We hope this may eventually ease the negative public preconception of timber and contribute to the adaptation of MET buildings in tropical monsoon climates.

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