Research Summary

bmtrada
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Cross-laminated timber and moisture



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ISBN: 978-1-909594-92-0

Research Summary

Introduction

Over the past decade, cross-laminated timber (CLT) buildings have been making headlines in the UK and international construction press. Completed in 2009, Stadthaus in Murray Grove, London became the world's tallest residential timber building at nine storeys, 29m tall. This was exceeded by Forté Living in Melbourne, Australia in 2013 at more than 32m tall, followed by Mjøstårnet in Brumunddal, Norway in 2019 at 85m tall. Others set to exceed this height are now under construction.

At the other end of the spectrum, Dalston Works in London boasts the largest square meterage of CLT. These CLT building systems are now commonly being used in the construction of large commercial, retail and educational buildings.

A common thread among all of these types of buildings is the length of time during construction that parts of the CLT structure are exposed to the prevailing weather; the larger and more complex the building, the greater the risk of wetting during construction.

Through BM TRADA's timber consultancy service we have been engaged on numerous projects where CLT roof and wall panels have become wet during construction. Once closed in with foil-faced insulation and overlaid with roof or other impermeable coverings, drying has been severely restricted, resulting in long-term wetting and the formation of fungal decay within the panels.

During discussions with Stora Enso we agreed to undertake a programme of research work to:

- determine the mechanism and extent of water uptake when CLT panels are exposed to wetting
- evaluate the effectiveness of temporary preventative strategies to minimise risk
- investigate how panels dry when wet.

The programme was divided into two phases:

- Phase 1 consisted of assessing ways to protect CLT panels from wetting during construction.
- Phase 2 consisted of investigating the most effective ways to dry panels if they get wet.

Phase 1: introduction

The purpose of Phase 1 was to:

- assess water uptake during construction
- investigate methods for reducing risk.

Through discussions with Stora Enso, and our experience of commercial projects, we decided to investigate the:

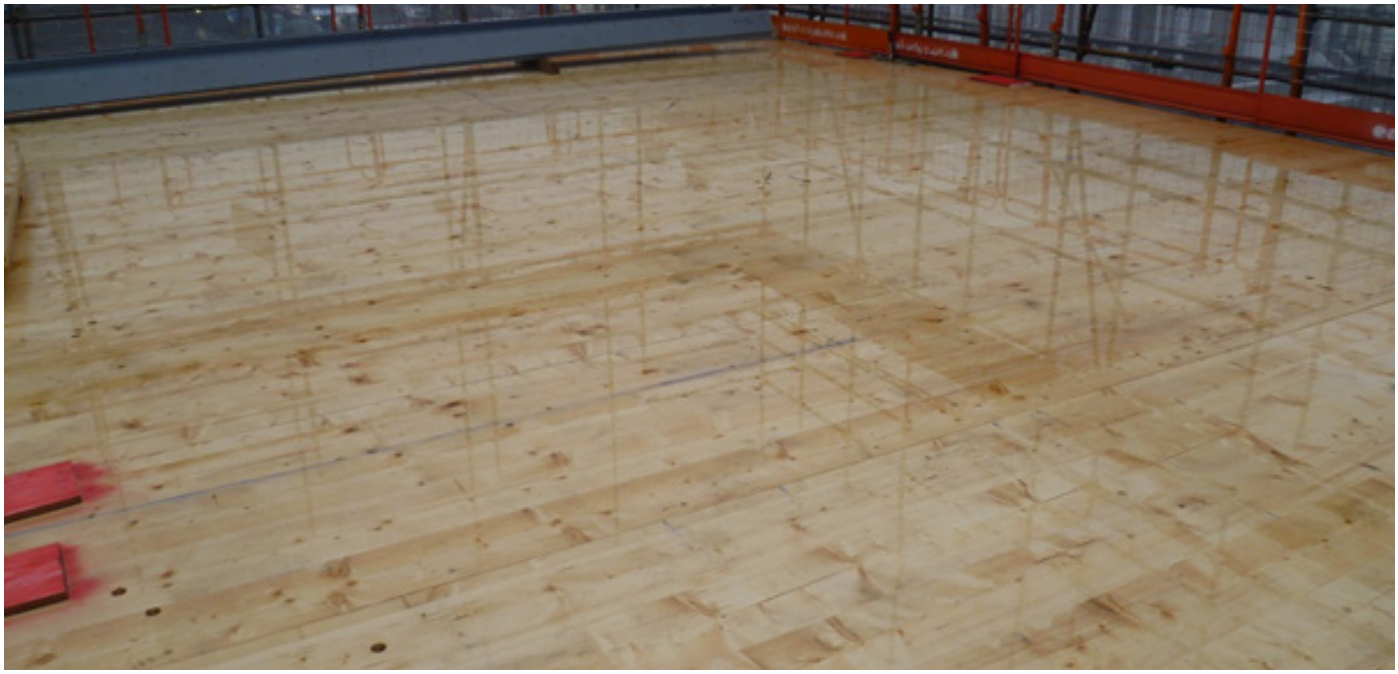


Figure 1: Horizontal CLT panel exposed to wetting during construction

- use of end-grain sealers to protect joints
- use of end-grain sealers to protect the face of panels
- use of adhesive tapes to protect joints
- use of a temporary protective membrane
- influence of joint type
- influence of wetting regime.

Horizontal panel joint type

The three main types of panel joint are butt, half-lap and spline. Different panel joints have differing surface areas and therefore potentially different risks of wetting. Stora Enso confirmed that the most common types of panel junction they produce are half-lap and butt joint so we selected these types for testing. If a third joint type had been tested, it would have exceeded the limit on the number of panels we could accommodate.

Self-adhesive tape

Depending on the CLT system being used, joints between panels are often sealed with adhesive tape to provide a line of airtightness to the structure. During construction this tape can limit the water ingress into joints. In test panel configurations where tape was used to seal joints, we applied it to joints between horizontal panels and to the 90° joint between the vertical and horizontal panels.

End-grain sealant

There are several different types of end-grain sealer available, ranging from thick wax products typically applied with a palette knife, to lower viscosity liquid products applied using a brush, roller or spray.

A medium viscosity product that could be applied with a brush or roller was selected for the tests, on the basis that thicker products would be difficult to apply in a commercial setting and thinner products tend to offer less protection. Small-scale laboratory testing was carried out comparing the performance of two different end-grain sealers (one suggested by BM TRADA and one suggested by Stora Enso). Similar performance was observed between the two products, although one product performed slightly better than the other. Two-coat applications provided substantially better performance than one coat.

All panels had their three outer edges (i.e. all edges not in contact with another panel) coated with two coats of end-



Figure 2: Overview of test rigs during setup; 14 of the total 22 test rigs are shown

grain sealer to limit drying through their edges – to simulate them being part of a larger panel. Where panel joints and panel faces were coated with end-grain sealer, they received a single coat; in a commercial application, it is unlikely that panel manufacturers would be able to apply two coats due to the necessary speed of panel fabrication and sealer drying times.

Wetting regime

A worst-case scenario of frequent wetting and a medium-case scenario of infrequent wetting were selected to try to capture the potentially variable nature of site conditions. Each combination of protective measures was duplicated with two test rigs, one receiving water every two days (frequent wetting) and the other set of panels receiving water every two weeks (infrequent wetting). Data presented in this summary shows the results from frequent wetting rigs – infrequent wetting rigs showed similar results, albeit at lower overall moisture contents.

The average UK annual rainfall is 1419mm, which equates to an average daily rainfall of 3.9mm, based on Met Office data taken between 2001 and 2019. For each wetting event approximately 8mm of water (two days' rainfall) was applied to the top of each test rig. Plastic dams were installed around the edges of horizontal panels to contain the water and prevent it flowing over the outer edges, to simulate the type of standing water that we have observed on some construction sites. Test rigs were placed in a covered timber drying shed open to the prevailing weather but protected from unintended wetting. The only water coming into contact with the panels was that specifically applied to them.

A red trace dye was added to help visualise the wetting of panels. Once testing was completed, panels were dissected to allow a visual examination of the absorption of water at panel joints (and to a lesser extent within the field of the panels).

Temporary protection membrane

The use of a temporary weather protection membrane may limit the wetting of horizontal panels during construction but may be susceptible to damage and leaks at joints.

A poorly fitted/damaged temporary protection membrane was installed on two of the test panels. We decided not to test a well-fitted membrane because, installed in perfect laboratory conditions, a well-fitted membrane would have prevented wetting; dry panels would not have provided valuable data. The reality of construction sites means that leaks at membrane junctions and mechanical damage are almost inevitable with loose-laid membranes. Fully bonded membranes were not tested.

Phase 1: findings

Field of panels compared to joints

In CLT buildings under construction, our site survey team observed that moisture uptake was greater at panel junctions than within the field of panels – this is due to the presence of exposed end-grain and greater surface area within the joint. When fungal decay is found, it tends to initiate at panel junctions and so investigating protection to joints was one of the main objectives of this work.

Figure 3 shows water uptake within the top lamination in the field of panels compared to at panel joints, and was taken from test rigs with no specific protection measures to either.

Panel joints absorbed more water more quickly than the field of panels; in this testing, the average moisture content of joints exceeded 20% after five days with a maximum average of 30%, while the field of panels took 22 days to exceed an average moisture content of 20%, with a maximum average of 22%.

The moisture content threshold for the development of fungal decay is 20%. If timber remains at a moisture in excess of 20% to 22% for an extended period of time, surface mould and wood-rotting fungus can propagate.

Joint type

Each test rig was duplicated with both a half-lap and a butt joint to investigate whether different joint types had a greater or lesser risk of water uptake. Due to space limitations, it was only possible to test two joints, but it is likely that spline joints would behave in a similar manner to half-lap – both of which have a larger exposed surface area and greater risk of trapping water compared to a simple butt joint.

Figure 4 shows the average moisture content in the top three laminations at the two different joint types taken from panel joints with no protection. A similar pattern of moisture distribution was also observed where joints had additional protective measures, albeit at lower overall moisture contents.

Half-lap joints absorb water more quickly than butt joints, but over an extended period of time both joint types achieved a similar average moisture content. Half-lap joints exceeded an average moisture content of 20% after four days, while butt joints exceeded an average moisture content of 20% after 17 days. After the first month, both joint types had similar average moisture contents in the top three laminations.

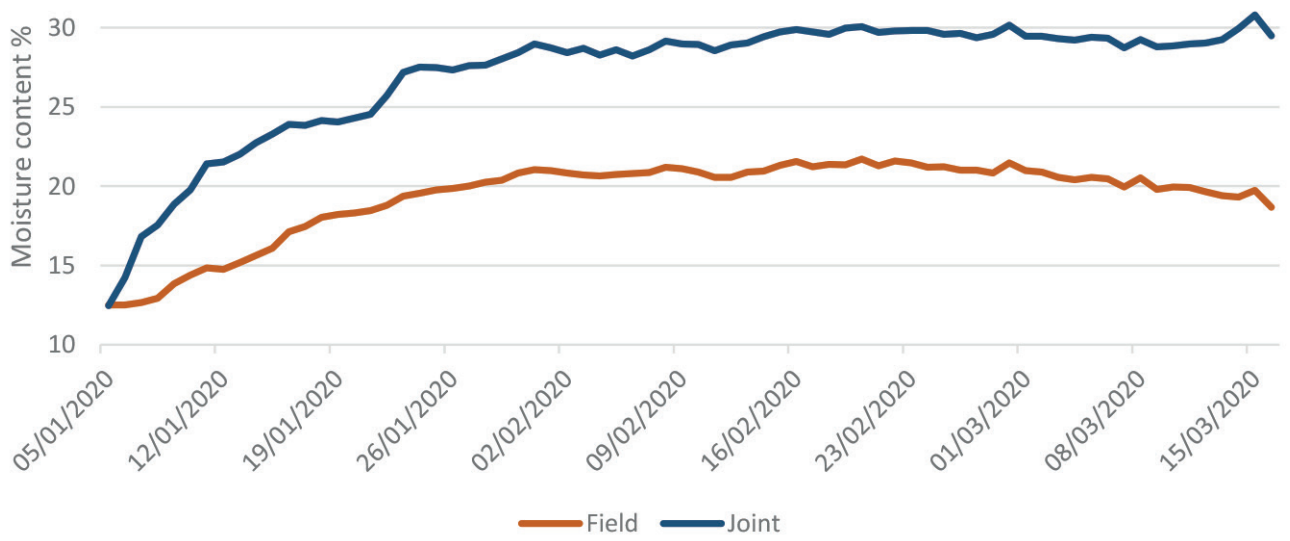


Figure 3: Average moisture content readings in the top lamination at panel junctions and within the field of panels

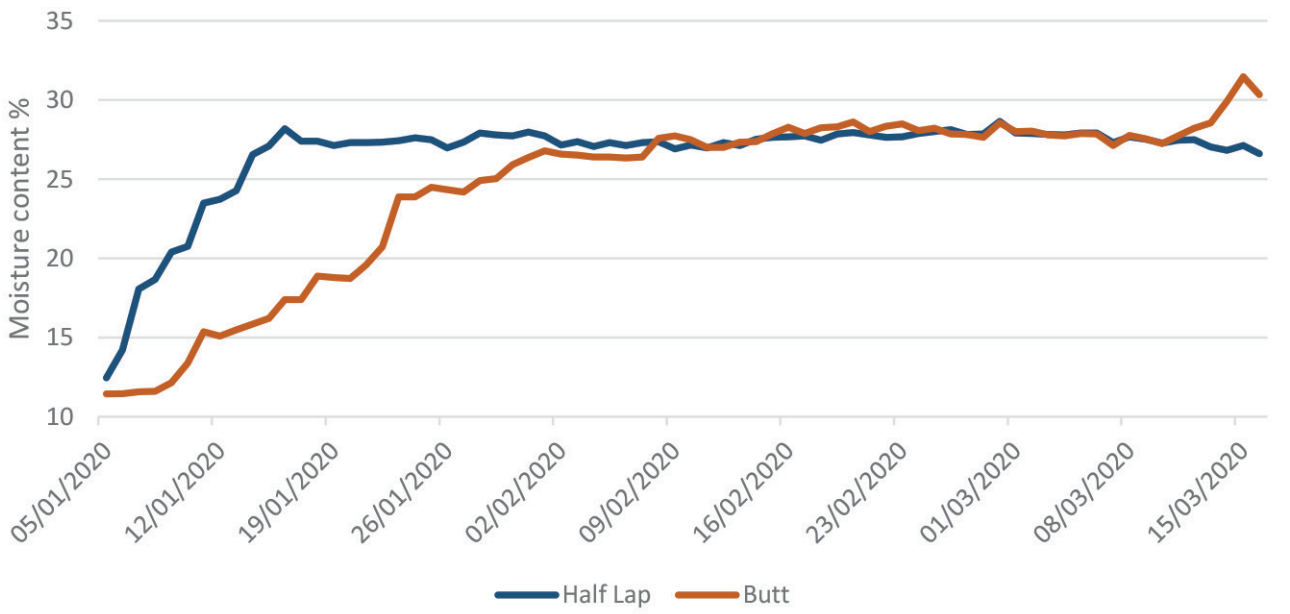


Figure 4: Average moisture content readings in the top three laminations at the two different joint types in panels with no additional protective measures

End-grain sealer to joints

Comparing panel junctions protected with end-grain sealer against unsealed panel junctions showed both a reduction in water uptake and a reduction in maximum moisture content over the 70-day test duration.

Figure 5 shows the average moisture content at panel junctions sealed with a single coat of end-grain sealer compared to unsealed panel junctions. Data from half-lap and butt horizontal joints and 100mm up from the base of wall panels have been used. Moisture content readings in horizontal panels have been taken from the top three laminations; moisture content readings in the walls have been taken from a face and a middle lamination.

At unsealed panel joints, moisture content readings ranged between 18% and 60%, while moisture content readings at sealed joints ranged between 15% and 42%, with average moisture contents reaching 30% and 23% respectively.

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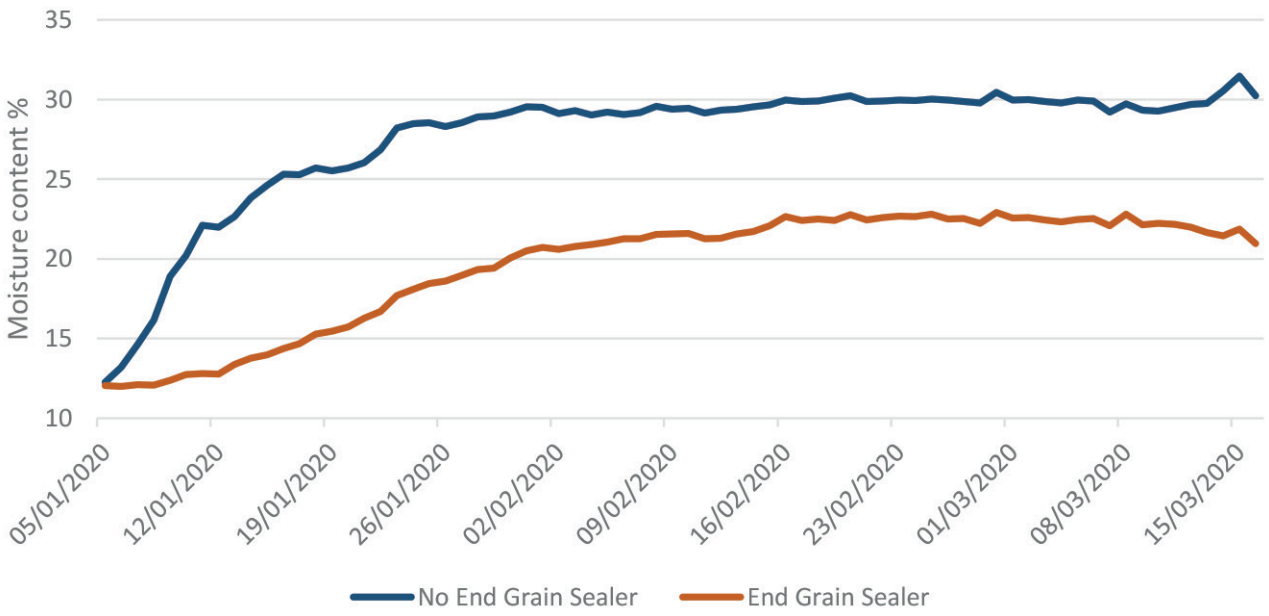


Figure 5: Comparing average moisture content readings in the top three laminations at joints with no protection and joints with end-grain sealer

In addition to the observed reduction in moisture uptake, the average moisture content at unsealed joints exceeded the fungal decay threshold of 20% after five days, whereas it took 25 days for the average moisture content of sealed joints to exceed the same threshold. Looking at individual panel moisture contents, the first unsealed panel edge exceeded 20% within 24 hours, whereas it took eight days for the first sealed panel joint to exceed 20% moisture content.

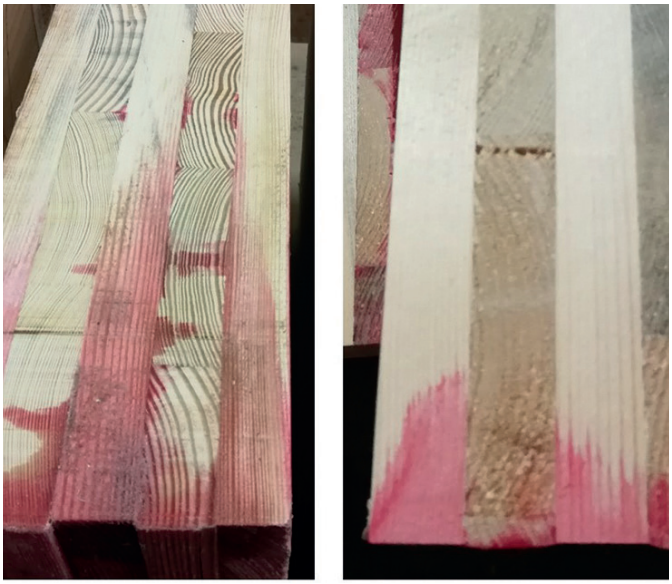


Figure 6: Vertical section through panel showing absorption along panel (wetting to bottom edge). Unsealed left, sealed right

After completion of the testing, panels were dissected to inspect water distribution. *Figures 6* and *7* show the comparison between unsealed and sealed panel edges. In all cases, less water travelled a shorter distance into panels with end-grain sealer applied to the edges compared to unsealed panels.

Joint tape

Comparing panel junctions protected with adhesive tape against untaped panel junctions showed mixed results. *Figure 8* shows the average moisture content at horizontal



Figure 7: Section across panel showing distribution of water 50mm from joint. Unsealed top, sealed bottom

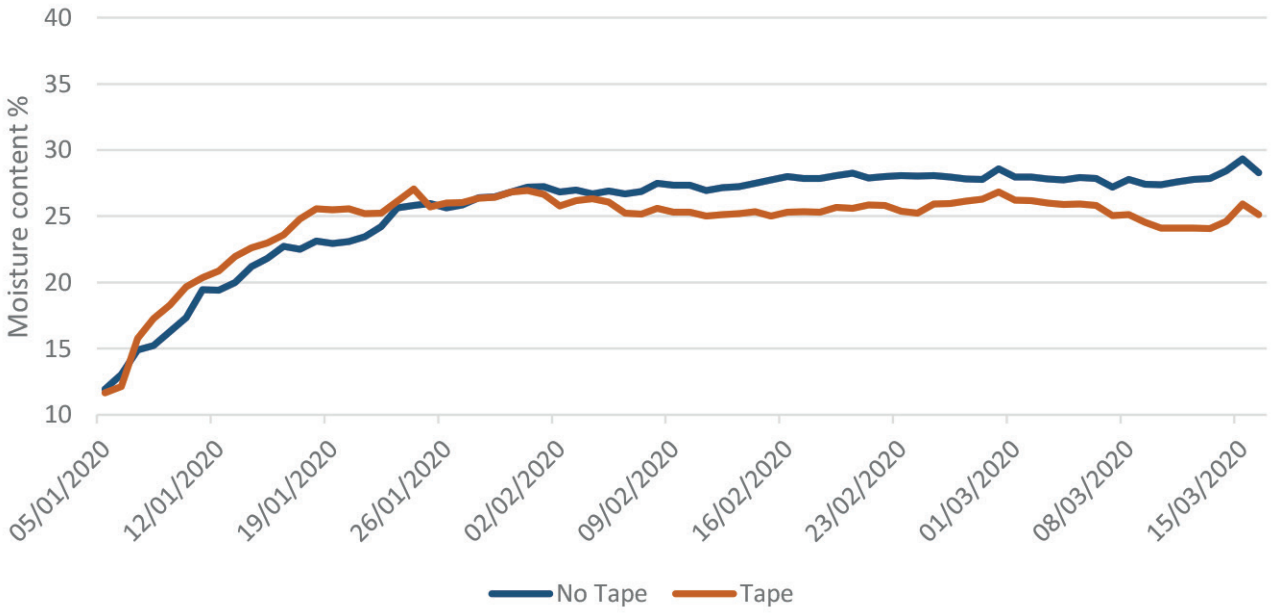


Figure 8: Average moisture content readings in the top three laminations at horizontal panel joints

panel junctions sealed with tape compared to untaped panel junctions. Data from half-lap and butt horizontal joints have been used. Moisture content readings in horizontal panels have been taken from the top three laminations. Data from wall panels is presented separately in *Figure 9*.

The data from horizontal panel joints showed little difference in moisture uptake between panel joints sealed with tape compared to untaped joints. However, from the data and from observations during testing, test rigs with taped joints allowed water to pond on the top surface compared to untaped rigs where water was able to drain through the joints. As a result, test rigs with taped joints achieved higher moisture content readings in the top laminations, which offset the reduced moisture contents observed in laminations two and three.

At the junction of vertical and horizontal panels, taping of the joint had a significant positive impact on moisture content

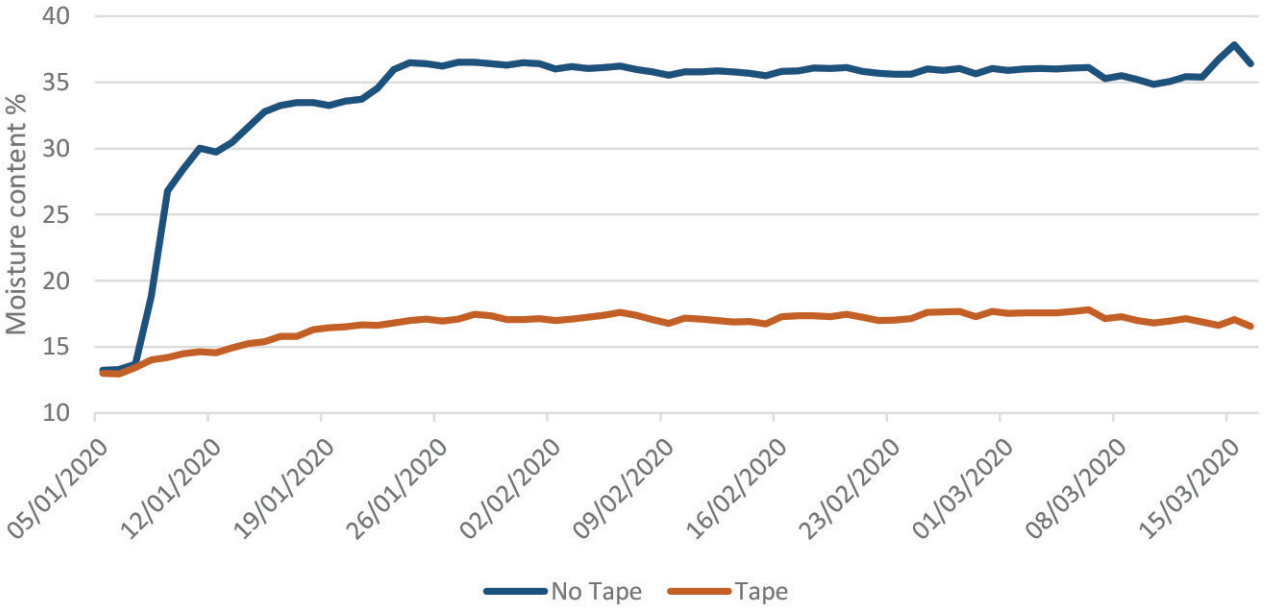


Figure 9: Average moisture content readings 100mm up from the base of wall panels

readings within the wall panels, where water ponding was not directly in contact with the walls, as shown in *Figure 9*.

These findings show that the correct application of self-adhesive tape to panel joints can help to limit water uptake at joints, particularly to walls and pitched/sloping panels. However, if left unmanaged, tape will increase the risk of standing water on the top of flat panels as there will be less opportunity for water to run off, resulting in an increased risk of elevated moisture content.

Temporary protection membrane

A polythene damp-proof membrane was installed over the face of the horizontal panels and lapped up the base of vertical wall panels. Gaps around the edges of the membrane were not sealed, thereby allowing some of the water applied to the panel to leak around edges and gain access to the CLT panel below. This was intended to represent a site-installed, loose-laid temporary membrane with poorly sealed joints and/or mechanical damage.

Figure 10 shows that the poorly fitted temporary membrane does provide some protection against wetting for the first 30 days, after which the moisture content readings continue to rise above panels that had no protection membrane fitted. This finding appears logical – the temporary membrane, even poorly fitted, will limit direct wetting compared to uncovered panels. However, over an extended period of time, the membrane will also prevent the panel drying when conditions allow.

Temperature

This wetting phase of testing was carried out between January and March 2020 – i.e. during the winter. At first glance, this may appear to present a worst-case scenario – cold and wet weather with panels subjected to regular wetting. However, higher temperatures and solar gain in spring and summer hold the potential for both reducing water uptake through drying between wetting events and also increasing vapour transmission through the thickness of panels, resulting in a higher uptake of water. BM TRADA has previously seen evidence of this in its commercial consultancy work.

A small-scale lab test was undertaken to assess the impact of temperature and solar gain on the wetting of panels. Panels were regularly wetted using a similar regime to that of the full-scale panels outside.

- Panels were held at a 'low' air temperature of approximately 6˚C with a relative humidity of approximately 85%; a rough approximation to the external conditions of the full-scale panels outside.
- Panels were held at a 'medium' air temperature of 20˚C, with a relative humidity of 65% in our conditioning rooms.
- One pair of panels were held at an air temperature of 20˚C, with a relative humidity of 65% and an infrared heat lamp positioned above them to simulate solar gain. The heat lamp was timed to be on for 12 hours and off for 12 hours to represent day and night.

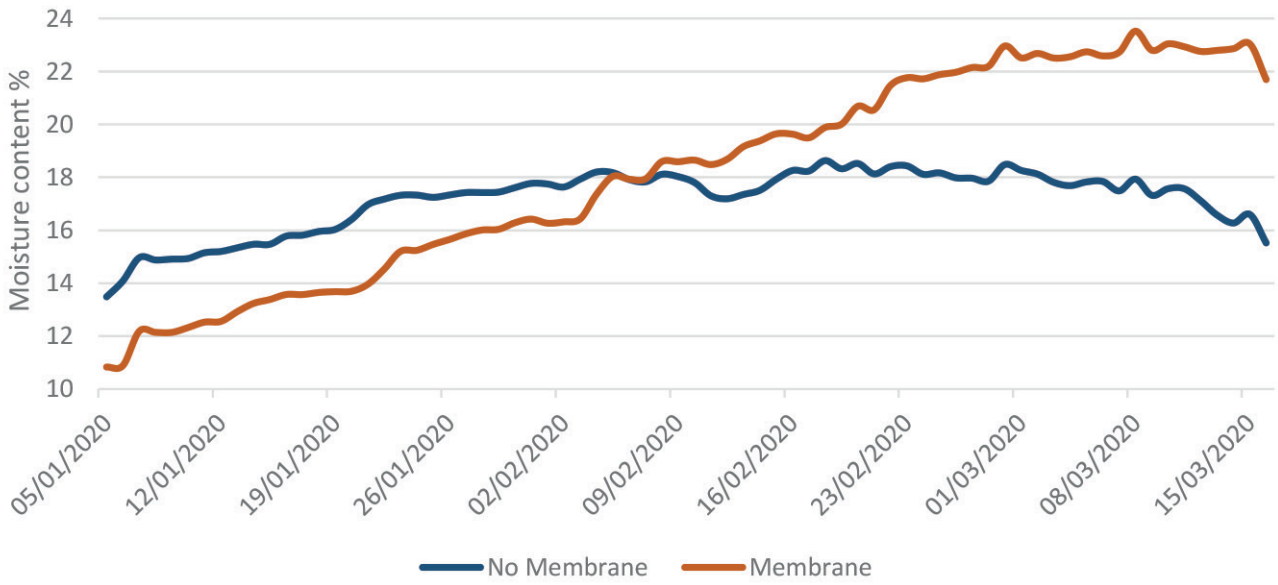


Figure 10: Average moisture content of the horizontal panel top laminations. Graph shows an average of readings taken from joints and in the field of panels

Results from the low temperature panels in the lab were consistent with those observed on the full-scale panels outside; the top surface of the panel remained damp for the duration of testing. The warm panels were normally visibly moist but without liquid water on the surface. The panels exposed to solar gain were visibly dry and warm to the touch before the reapplication of water.

Figure 11 shows the comparative moisture content readings in the top lamination of the 'cold' control panels compared to the 'warm' panels and the panels exposed to solar gain. The peaks in the graph correlate with the infrared heat lamp warming the top surface of the panels (12 hours on, 12 hours off).

Based solely on visible observations of the panels throughout the wetting process, it could be said that the panels exposed to solar gain appeared to be dry while the cold panels were visibly wet, despite potentially having similar moisture contents in the middle of the top lamination. A contractor on

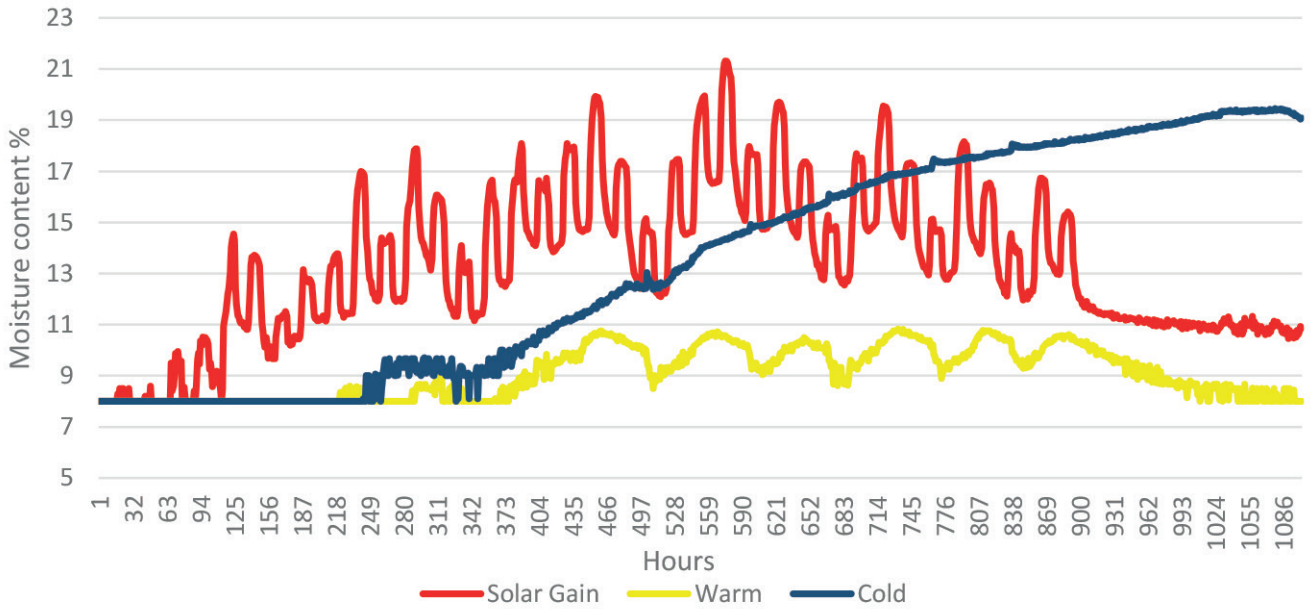


Figure 11: Cold, warm and hot panels. Peaks in solar gain line coincide with heat lamp cycle. Heat lamp turned off after 900 hours

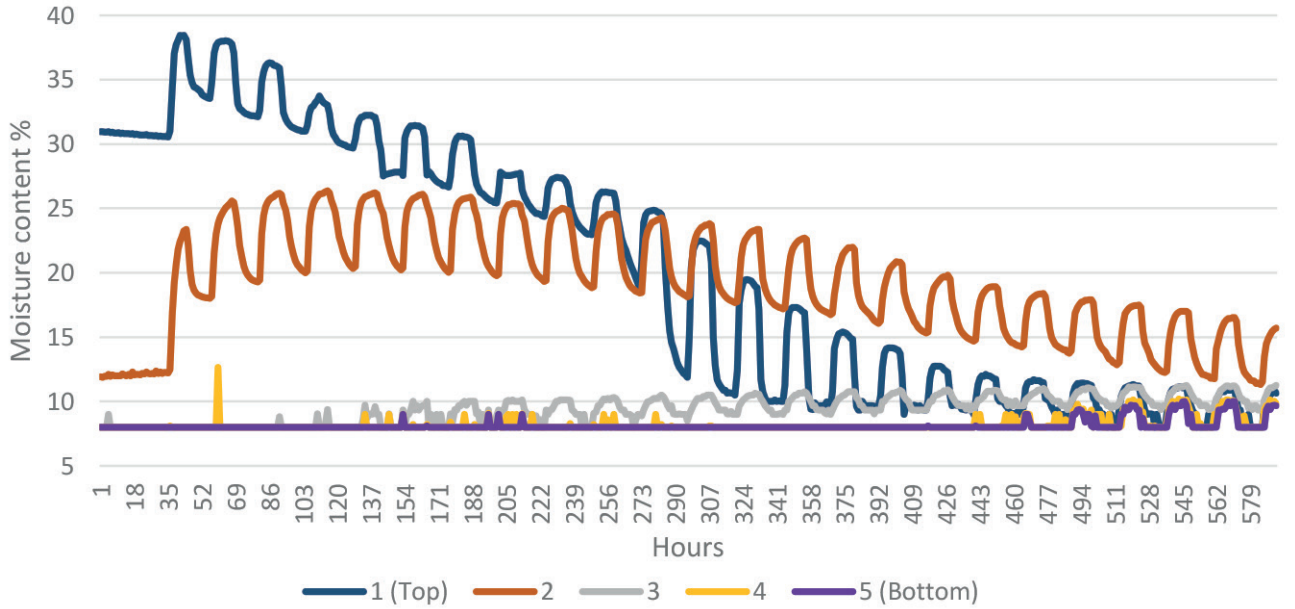


Figure 12: Moisture content readings in a wet panel subsequently exposed to solar gain. 12 hours of solar gain followed by 12 hours of resting. 1 was the top (wet) lamination, 2 the second, 3 the third, 4 the fourth and 5 the bottom lamination.

site may look at the panels exposed to solar gain and surface drying from the sun and believe that the panels were dry. However, looking at the first half of the graph in *Figure 12*, the application of heat to the surface of wetted panels results not just in evaporative drying of surface moisture, but a far higher rate of moisture vapour diffusion into the panels; this results in more rapid wetting of the top lamination.

This was also observed when solar gain was applied to panels that were already wet. While the outer lamination dried, moisture from that lamination was passed down through the laminations below (L1 was the wet lamination, L2 the second and so on, with L5 being the outer lamination on the dry side). Moisture contents in the second lamination rose quickly when the already wet outer lamination was warmed, as shown in *Figure 12*.

This phenomenon was further investigated in Phase 2.

Phase 2: introduction

BM TRADA timber consultants identified a research paper with a drying time calculation for American red oak (a relatively permeable hardwood) to allow kiln operators to assess potential drying rates of boards. The drying time equation used several 'drying constants' that had been determined for American red oak using empirical observation. Further research was undertaken to try to identify any drying constants for other timber species, but none were discovered.

The consultancy team undertook some initial example calculations using this equation with promising similarities to the observed drying rates of CLT. However, the drying constants presented in the paper for red oak did not provide a strong correlation with drying data identified for CLT.

As a result, a modification was made to the original scope of work in which large 1200mm x 600m CLT panels (in a similar configuration to those used in the Phase 1 testing) were to be wetted and exposed to a limited number of drying conditions. BM TRADA instead proposed that laboratory work would be undertaken to validate the drying model for CLT. In addition, a greater number of smaller CLT test blocks would be exposed to a larger range of conditions, thereby providing a wider spread of test results and hopefully providing a broader picture of the factors that influence drying time.

Two batches of tests were undertaken:

- 300mm x 300mm blocks of 100mm-thick five-layer CLT
- 75mm x 75mm boards 18mm and 44mm thick.

75mm x 75mm boards

Basic material drying tests were undertaken to establish baseline data and drying constants for European whitewood. To achieve this, planed, square-edged boards of 18mm and 44mm thickness were sourced and machined into 75mm x 75mm samples.

Samples were processed using a vacuum wetting technique to obtain a uniform and consistent wetting. Using this method, moisture content readings (by weight) were between 150% and 200%, i.e. complete saturation of the samples.

Once wetted, the edges of all boards were wrapped in self-adhesive plastic tape to prevent rapid drying from edges and ends. In some cases, one face of the boards was also covered in tape to force boards to dry from one face only, effectively doubling their thickness and simulating the restricted drying pathways of laminations within CLT panels.

300mm x 300mm CLT blocks

Due to the use of trace dyes and variable exposure to wetting, the panels used for Phase 1 were not suitable for re-use in Phase 2. New 300mm x 300mm CLT blocks were cut from new panel blanks. Testing in Phase 1, as well as evidence gained from site inspections, showed that the highest moisture content readings in wet flat roof panels are most commonly found in the top lamination. To concentrate wetting into the top lamination, each of the test blocks had all four edges of the 'bottom' four laminations sealed with two coats of end-grain sealer, i.e. the top lamination had its edges exposed. The purpose of the end-grain sealer was to limit water uptake into the blocks except for the outer 'wet side' lamination.

Once sealed, the blocks were placed upside down in water such that the entirety of the unsealed outer lamination was submerged. Regular checks of moisture content were carried out and blocks were removed for testing when sufficiently high readings were achieved.

Once sufficiently wetted, blocks were removed from the water and the edges tightly wrapped in a self-adhesive aluminium tape (leaving the faces exposed) to avoid rapid drying from the ends and edges. Moisture content probes were installed into the centre of each lamination from the dry side of the panel positioned in the middle of the block and connected to data loggers.

Drying regimes

Samples were exposed to various different conditions to assess the effects of different drying regimes. The selection of

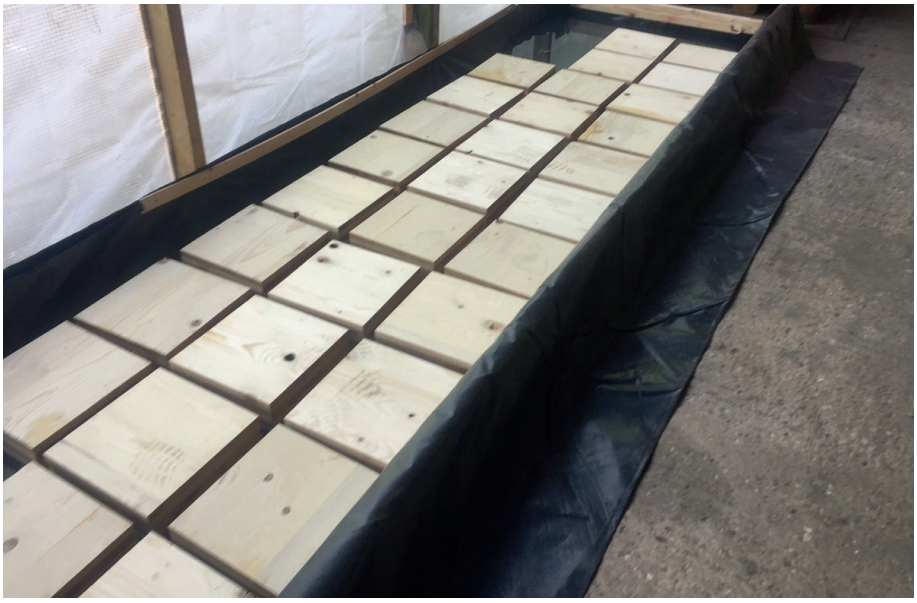


Figure 13: CLT test blocks partially submerged in water to artificially wet one outer lamination

conditions was based on those experienced on site, found in heated and occupied buildings, and elevated temperatures representing likely accelerated drying conditions. Test conditions were also partially dictated by the availability of conditioning rooms (BM TRADA has two climate-controlled rooms) and the availability of drying ovens and refrigerators.

CLT test blocks were exposed to the following conditions:

- ≈7°C, ≈70% relative humidity (RH)
- 20°C, 65% RH
- 30°C, 60% RH
- 40°C, ≈30% RH

Sample boards were exposed to the following conditions:

- 20°C, 65% RH
- 30°C, 60% RH
- 40°C, ≈30% RH

CLT test blocks were also exposed to temperature gradients to simulate likely site-based conditions during artificial/accelerated drying, i.e. heat applied to one face of the panel to more rapidly dry samples. The following temperature gradients were used:

- ≈7°C, ≈70% RH to 20°C, 65% RH
- 20°C, 65% RH to 40°C, ≈30% RH

Drying rates – constant temperature

From both the 75mm x 75mm boards and 300mm x 300mm CLT blocks, baseline data for the drying rates of CLT panels were recorded at a range of temperatures. This data was used to validate the drying rate model and obtain empirical drying constants.

Figure 14 shows the relative drying rates of 44mm-thick 75mm x 75mm boards (selected as an example) at 20°C, 30°C and 40°C alongside the calculated drying profiles using the drying time calculation and derived drying constants. A generally good correlation was obtained – at some board thicknesses calculated drying rates were slightly faster, at others slightly slower. As an overall average, the correlation was reasonable.

For each 10°C increase in temperature, there was approximately a 40% to 45% reduction in drying time. A similar comparison was carried out for the electrical resistance data taken from a CLT test block with a similar pattern observed; a reasonable correlation between the actual and calculated values although slightly larger deviations in drying time were observed at certain temperatures – some slightly quicker, some slightly slower.

The Phase 1 testing ended in March 2020. While the intention had been to dismantle the Phase 1 test rigs, due to

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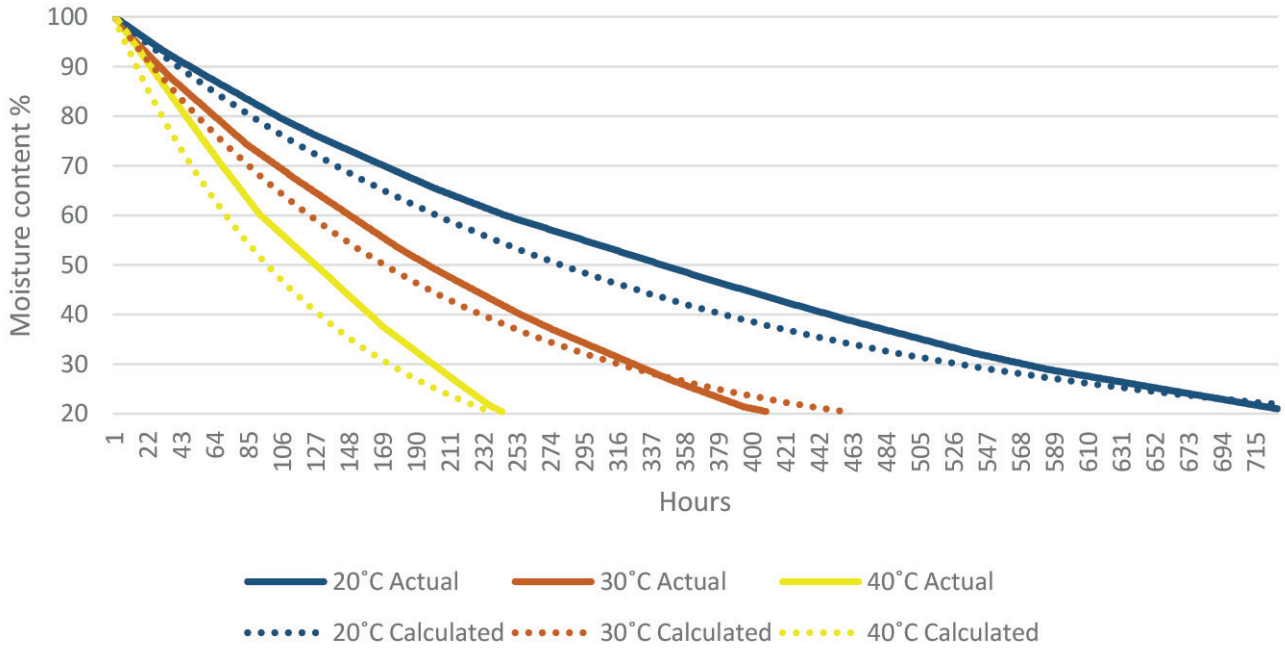


Figure 14: Relative drying rates of 44mm-thick, 75mm x 75mm boards exposed to various temperatures

unforeseen circumstances, the wet Phase 1 test panels were left to 'naturally' dry for several months before disassembly in the summer of 2020, with the data loggers still recording. This natural drying data also showed a good degree of correlation with the drying model.

Based on the validated drying model, the roles that temperature and relative humidity play on the rate of drying were investigated. *Figures 15* and *16* assume either fixed relative humidity with changing temperature, or changing temperature with fixed relative humidity.

The most important variable in the drying time of wet timber/CLT is temperature. Between relative humidity levels of 30% and 70%, there is a relatively small difference in drying times, considering the larger reductions that can be achieved by increasing temperature. If relative humidity is reduced from 70% to 30%, there is approximately a 33% reduction in drying time; 40% to 45% reduction in drying times can be achieved by increasing temperature by 10°C.

While reducing relative humidity will also influence drying time, there are some disadvantages that should be considered. Equilibrium moisture content is the moisture content that timber will naturally achieve at a given temperature and relative humidity. For example, a temperature of 20°C, 30% RH will result in a timber moisture content of approximately 6%, and 70% RH will result a moisture content of approximately 13%.

Equilibrium moisture content in a typical heated and occupied building is normally in the order of 12%. If, during drying, relative humidity levels are significantly reduced, the moisture content of the surface of CLT panels will also fall below the anticipated in-service equilibrium moisture content, increasing the risk of the development of surface spits and fissures for limited benefit in drying time.

In *Table 1*, reducing relative humidity while retaining colder winter air temperatures would result in a reasonable reduction in drying time – down from 123 days to 78. However, the upper surface of the CLT flat roof panel would dry down to an equilibrium moisture content of around 6%. This is a far lower moisture content than the panel would likely reach in service, and may increase the risk of development and size of surface splits and fissures due to shrinkage.

Whereas if the air temperature is increased to 20°C while maintaining a reasonably high relative humidity, the resultant moisture content in the surface of the panel will be broadly the same as the anticipated in-service moisture content, while reducing drying times down to 63 days, or down to 22 days if air temperatures can be increased to 40°C.

The use of higher air temperatures along with higher relative humidity appears to be the most logical drying regime when considering time taken and the risk of over-drying the surface of panels. It is generally accepted that timber exposed to

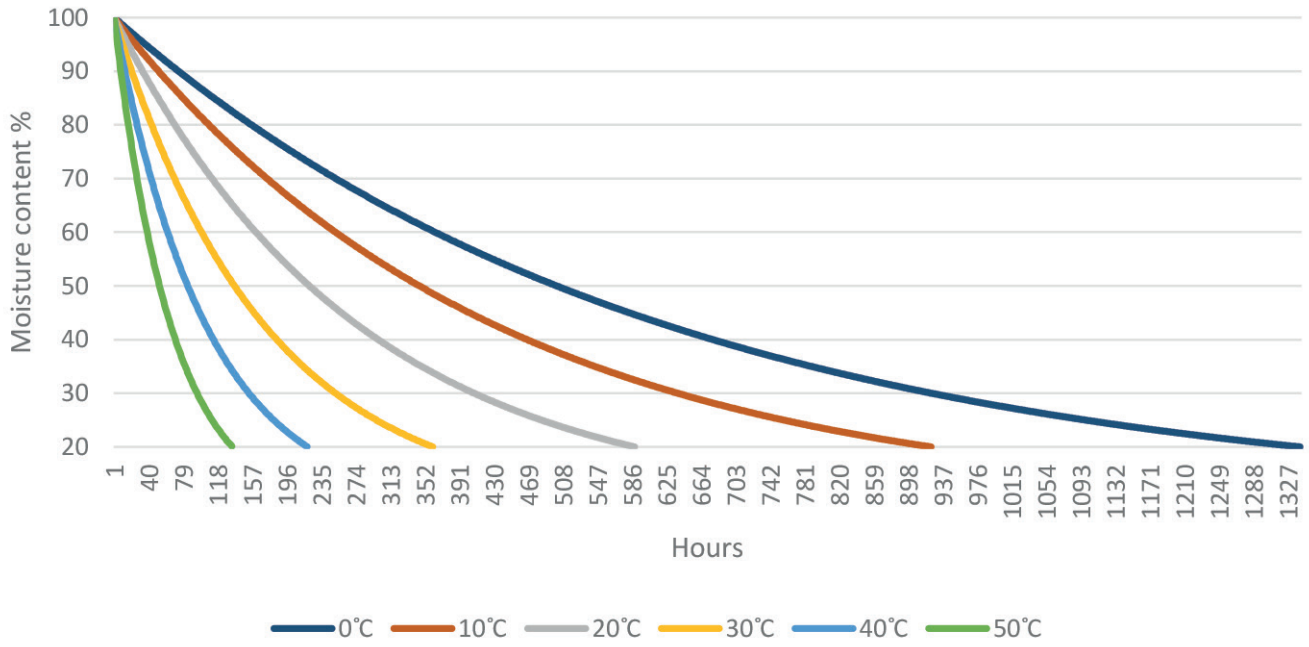


Figure 15: Drying profiles for varying temperatures at 50% relative humidity

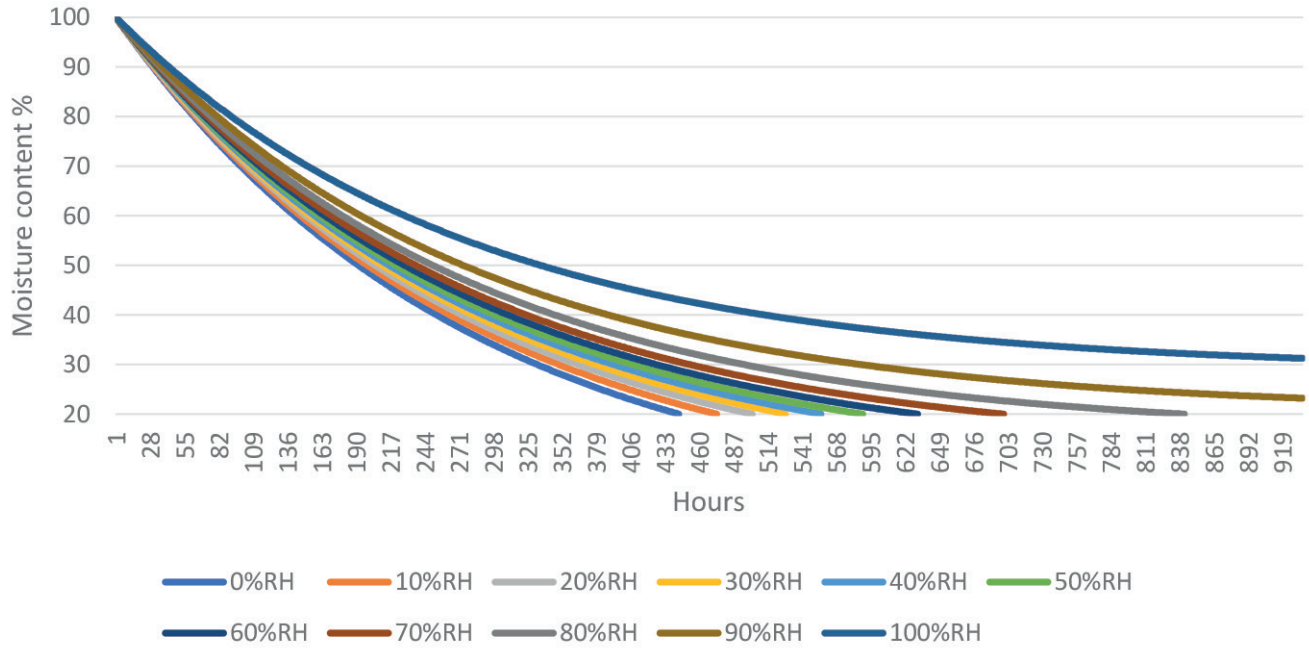


Figure 16: Drying profiles for differing relative humidity levels at 20°C

temperatures significantly in excess of 50°C for extended periods of time can result in a permanent loss of strength. Therefore it is recommended that a maximum temperature of around 40°C should not be exceeded during drying works. 40°C has been selected as a reasonable 'soft' limit, i.e. it is below the more critical temperature of 50°C and so provides some degree of tolerance for periods of time where heating systems may overshoot their target temperature.

Drying rates – covered panels

As well as testing the drying rates of bare CLT panels, tests were also undertaken to investigate the rate of drying when the wet surface of an element is covered with an impermeable membrane. In a typical warm flat roof construction, a high-resistance vapour control layer is placed over the top of the structural roofing elements, followed by rigid insulation (often

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Table 1: Example numbers for a CLT roof with various moisture contents at a depth of 40mm drying down to 20%

Example conditions	Temperature	Relative humidity	Equilibrium moisture content	Drying time in days. Moisture content readings at a depth of 40mm		
				35%	30%	25%
Example winter conditions	5°C	70%	13.5%	100	78	48
Example winter conditions and drying using low relative humidity (e.g. dehumidifiers)	5°C	30%	6.2%	62	46	26
Example winter conditions and drying using higher temperatures (e.g. recirculating heating)	20°C	70%	13.1%	51	40	24
Example winter conditions and drying using higher temperatures (e.g. recirculating heating)	40°C	70%	12.2%	18	14	8

foil-faced) and a waterproof roof covering. In this scenario, there is no opportunity for any excess water trapped in the upper surface of the panel to dry up to the outside; all excess moisture must pass down through the panel and dry into the room below.

On a more traditional timber joist flat roof with plywood or OSB deck, a typical 18mm-thick deck and timber joists have a large exposed surface area compared to their volume and thickness and so are able to dry rapidly once enclosed. On a CLT warm roof, the same principle is normally assumed – excess moisture within panels should be able to dry down into the room below.

However, BM TRADA consultants have undertaken numerous site inspections of live projects where CLT flat roof panels have been exposed to wetting during construction and been enclosed while still at a high moisture content. In several cases, we have been able to track the drying progress of these buildings over many months (and in one case years) and have seen that drying rates are sufficiently slow that panels are at risk of the development of fungal decay. We have also been involved in a number of projects where opening up works have been undertaken in completed buildings after a period of occupation, and upon exposing flat roof panels, areas of decayed but dry timber have been found. This indicates that they were exposed to wetting during construction and eventually dried out, but drying was slow enough to allow fungal decay to develop.

To assess the drying rate of covered panels, CLT test blocks were wetted in the top lamination and then overlaid with a high resistance membrane to represent a warm flat roof being closed in while still wet. Panels were then placed in our 20°C and 30°C conditioning rooms and monitored for 12 months. Initial moisture content readings on the top lamination of test panels were approximately 35%.

In panels drying at 20°C, it was found that over the first 9 months, moisture content readings in the top lamination remained stable and did not fall; between months 9 and 12, moisture contents started to reduce down to 20%. Moisture content readings in the second, third and fourth laminations were all found to gradually increase over the first 9 months (before slowly falling), indicating that moisture was moving down through the panel and drying to the underside.

In the case of the panels drying at 30°C, a similar pattern was found with the top lamination readings remaining stable while the moisture content readings of the lower laminations gradually increased. After six months, the moisture content readings in all laminations started to fall, with readings dropping to 20% after ten months.

Our prior experience of CLT buildings exposed to wetting during construction has shown that, if panels are exposed to wetting during construction and are enclosed at moisture contents over the fungal decay threshold, the development of decay such that it is identifiable in the timber (e.g. detectable/obvious loss of density) typically takes around 18 months.

After approximately six months, surface softening and the early development of fungal decay was identified in the panels drying at 30°C. In this testing, fungal decay did not progress much further than these early stages as panels started to dry with moisture contents reducing to below the fungal decay threshold after a total of ten months.

Based on our site evidence and the findings of this lab testing, CLT panels that have become wet during construction and are enclosed with non-breathable outer layers at moisture contents over the fungal decay threshold of 20% to 22% are

at risk of the development of fungal decay after approximately 9 to 12 months at 30°C and 18 to 24 months at 20°C. It should also be understood that moisture content, as well as temperature, has an impact on the rate of decay development and so it can be difficult to provide accurate estimations.

We observed that where wet panels are able to dry from the wet face, drying appears to occur in a sufficiently short period of time (up to four weeks at a moisture content of 35% in our laboratory testing) such that decay would be unlikely to be a risk. If non-breathable construction details are used (such as vapour control layers and/or foil-faced insulation to the outside of the panels) enclosing panels over a moisture content of 20% may result in drying rates sufficiently slow for fungal decay to be a risk. While not ideal, if breathable construction details are used (such as low water-vapour resistant insulation materials and other breathable materials to the outside face of panels), drying rates may be fast enough that the risk of significant decay to panels may be low if they are enclosed at moisture contents slightly above the fungal decay threshold of 20%.

Drying rates – temperature gradients

When drying wet CLT flat roof panels during construction, the typical approach often taken by contractors is to apply heat to the wet side of the panels by constructing an enclosure and conditioning the air within the space with heaters or dehumidifiers. When investigating the influence of temperature on drying rates (as discussed above), both sides of panels were exposed to the same temperature. In reality, when drying works are carried out on site, one side of the panel will be exposed to elevated temperatures while the other side of the panel will be exposed to ambient conditions. Previous experience of drying CLT panels indicated that these types of temperature gradients can result in moisture transfer into the panel from the wet face, increasing the moisture content of the second and third laminations.

To investigate this phenomenon, CLT test panels were exposed to temperature gradients in both directions, i.e. heat applied to the wet face and heat applied to the dry face. The purpose of testing gradients in both directions was to determine whether moisture was moving from hot to cold or from wet to dry.

From our laboratory testing, we observed that, where temperature gradients are present across the thickness of the panel, moisture within the panel will move from the warm side to the cold side. In test configurations where the wet face was heated, moisture from the top wet lamination would dry to the outside, but a portion of that moisture would also be driven down deeper into the panel causing an increase in moisture content in the second and third laminations. In test configurations where the dry face was heated, moisture would quickly move out through the wet colder lamination to the outside and so not increasing the moisture content of the rest of the panel.

Under ideal circumstances, wet CLT panels would be allowed to dry exposed to the same conditions on each side – this arrangement typically provides the fastest overall drying rates. If wet CLT panels are to be dried during the warmer summer months, it may only be necessary to prevent further water ingress into the top of the panels and allow the timber to dry exposed to the warm ambient air on both sides of the panel. During the colder winter/spring/autumn months, drying rates can be increased by raising the air temperature if the predicted natural drying rates are too slow to be accommodated in the build programme – this may also be the case during the summer if drying rates are still too slow.

Ideally, where air temperatures are artificially elevated, this warmed air is applied evenly to both sides of the panel so that the fastest drying rates can be achieved. If the structure below is enclosed, the building should be heated and an enclosure constructed above the roof panels and also heated to a similar temperature.

It is important to consider the risk of moisture transmission deeper into the panel before drying works are undertaken and to monitor this as works progress. Given the significant increase in drying times that occur as moisture penetrates deeper into timber, unintentionally increasing the moisture content of lower laminations through moisture diffusion may significantly increase the overall drying time for the panels.

Phase 1: conclusions

- End-grain sealers can be used to protect joints between horizontal panels and joints between horizontal and vertical panels. A single-coat application can reduce water uptake at joints. A two-coat application will provide greater protection, but may not be practical in a commercial setting. However, when used in this type of application, end-grain sealers do not act as a complete barrier to moisture and so the moisture content of panel junctions may still exceed the fungal decay threshold of 20% if wetted over an extended period of time.
- Butt joints had a slower initial rate of water uptake when compared to half-lap joints, but achieved similar moisture levels over time. When coupled with end-grain sealer, butt joints had much slower rate of water uptake.
- The use of self-adhesive tapes can be both beneficial and problematic. On sloping or vertical surfaces, and the junction between vertical and horizontal panels at the base, correctly applied tapes can provide a good defence against

wetting. However, when applied to horizontal panels, water is more likely to stand rather than drain through joints, resulting in generally higher moisture contents in the top lamination. Where tapes are to be applied to flat roofs, the site moisture management plan should consider this.

- Standing water should be removed from panels as quickly as possible (at least daily if not twice daily), by brushing water away or preferably by designing flat roofs to have a sufficient fall to cause rapid and effective drainage; in this case, tapes would prove beneficial.

- Loose-laid temporary waterproofing membranes reduce water uptake for a short period of time. However, over a longer timescale, loose-laid temporary membranes risk trapping moisture below them causing higher moisture content readings. Solar gain on dark coloured membranes is likely to increase the risk of excess moisture absorption. Loose-laid temporary waterproofing membranes should be avoided. BM TRADA did not undertake testing on bonded systems.

- Solar gain in warmer summer months can dry the surface of the panels. However, under certain conditions wetting and solar gain can result in a more rapid uptake of moisture into panels than in colder/less sunny conditions. Our testing indicates that the risk of excess water absorption could be similar between summer and winter, although this will depend on the regularity and amount of rainfall – regular rain showers and warm sunshine may prove to be as problematic as cold and wet winter conditions. The moisture content of a panel should not be assumed based on whether the surface looks wet or not.

Phase 2: conclusions

- We used a drying time model found during a preliminary literature survey to predict the drying time of timber. Variables used in this model were established for CLT and solid timber test blocks of different thicknesses exposed to different drying conditions.

- Under test conditions, increasing drying temperatures reduced drying times. For each 10°C increase in temperature, a reduction in drying time of approximately 40% can be achieved.

- While relative humidity does have an impact on drying rates, its influence is less significant when drying down from a high moisture content. Drying rates slow as timber approaches equilibrium moisture content. Lower relative humidity levels result in lower equilibrium moisture content and so this slowing occurs later – this is less of an issue where the drying target is the fungal decay threshold of 20%. Low relative humidity results in low equilibrium moisture content increasing the risk of the formation of splits and fissures in the face of panels.

- In all configurations where the wet side of the CLT test panel was able to dry, drying occurred in a relatively short period of time (up to four weeks). However, where the wet face of the panel was covered, drying was far slower (over 12 months). In wet CLT flat roof panels covered with a vapour control layer, drying of the top, wet lamination down through the full thickness of the panel could potentially take several years depending on panel thickness and moisture content.

- Where drying takes longer than 9 to 12 months at 30°C and 18 to 24 months at 20°C, the CLT panels will be at risk of the development of fungal decay. If wet CLT flat roof panels are enclosed with non-breathable materials at a moisture content above 20%, they will be at risk of the development of fungal decay.

- To help reduce the risk of the development of fungal decay as a result of trapped construction moisture, breathable constructions should be used (i.e. breathable insulation materials with no separate high resistance vapour control layer). Where panels are able to dry from their wet face (without moisture having to pass back through the full thickness of the panel), drying times may be fast enough to mean that the development of fungal decay would be unlikely. While we do not recommend that wet panels are enclosed, a balanced and considered view of the technical and commercial risks could be taken on a case-by-case basis, but only if designs can breathe on the outside and only where moisture content readings are slightly over the fungal decay threshold of 20%.

- Breathable wall and pitched roof designs using insulation products with a low moisture vapour resistance are relatively common; however, designs for breathable and ventilated flat roof designs are more complex. In a traditional cold ventilated flat roof, roof spans are typically limited to 10m to minimise ventilation path lengths. If this path distance is to be maintained with ventilated CLT flat roofs, many additional mid-span vents may be required, particularly on a large commercial roof structures. The installation of these vents brings with it additional considerations and risks. Breathable insulation materials are normally compressible and so will usually require a secondary support structure to hold the roof deck above.

Summary

When embarking on a new CLT project, the building designer, with support from the CLT supplier, should consider the risks of

wetting during construction and develop designs or systems to mitigate the risk. Naturally it would be ideal and potentially more efficient to build all buildings (regardless of construction type) under cover, as prevailing weather can be detrimental to all construction types and build programmes. Perhaps in the future this method of working (sometimes used on the continent) may become a common sight in the UK. However, there is a cost and complexity to temporary enclosures that may be difficult for contractors in the UK to overcome. Where enclosures are not used, the building system, design and installation details will need to consider and be tolerant of our climate – often wet, regardless of the time of year.

The most common location where high moisture content readings are likely to occur is at the joints between flat roof panels, particularly where those flat roof panels are installed horizontally, as well as at the base of walls sat on horizontal surfaces. High moisture content values may also occur in floor panels, although they normally have ample time to dry once the building has been made weathertight; build sequence and the permeability of floor finishes should also be considered. If floors are to be overlaid with impermeable finishes early in the build sequence, slow drying and the risk of fungal decay may also be a concern.

The type and combination of protective measures may not be the same for all building types. Small, simple buildings with quick build programmes should not be exposed to the prevailing weather for a long period of time and so the risk of wetting will be relatively small. Large buildings will have much longer build programmes so the risks will increase considerably and more protection may be required.

Considerations

1. Assess whether falls to flat roofs can be created with the panels (rather than using cut-to-falls insulation). If panels can be sloped, water will run off more quickly, reducing the chance of it ponding/standing. Sloping flat roof panels may incur some additional cost and complexity as wall panels below will need to be fabricated with sloping top edges; however, flat insulation products can then be used (rather than cut-to-falls), which may offset some of that cost.

2. With consultation from the CLT engineer, consider the types of joints used between horizontal panels. Butt joints are faster and less expensive to fabricate compared to half-lap joints or splines, but may not offer the same structural performance. Metal nail plates or proprietary connectors can be used to connect butt joints together.

3. Where projects allow, it may also be prudent to consider building vertically rather than horizontally to limit the time areas of roof are exposed to the weather. Building in vertical cores and installing roof coverings can be practical on certain types of building.

4. Consider the specification of end-grain sealer products at panel junctions. Some CLT manufacturers, including Stora Enso, can apply end-grain sealers in the factory during fabrication. Where this is not possible, end-grain sealers can be applied during erection, although drying times and sequencing should be considered. Two coats of end-grain sealer offer substantially better protection than one coat, but drying times and panel handling may make the cost prohibitive.

5. Where joints between panels are sealed with adhesive tape for airtightness, consider water run-off, or lack thereof. On sloping and vertical panels, tapes provide protection. On horizontal panels, the risk of standing water is increased and this risk should be considered in the site moisture management plan.

6. Loose-laid temporary protection membranes provide some limited protection for a short period of time, but over an extended timeframe will likely result in higher moisture content readings in panels compared to panels that have no coverings. Fully bonded products may provide worthwhile protection as there should be no ability for water to pass between the panel and the membrane at edges and where damaged. However, BM TRADA did not carry out any testing on bonded products and so cannot offer any comparative performance data.

7. A site moisture management plan should be drawn up, with all parties involved in the project understanding their responsibilities. The management plan should consider mitigation measures, moisture content monitoring and trigger points where action should be taken. The moisture management plan may also contain regular tasks such as removing standing water from horizontal panels.

8. Both the CLT supplier/erector and the main contractor should agree a strategy for taking and recording moisture contents during construction. Moisture content readings should be taken at panel junctions and within the field of panel. They should also be taken at multiple depths using hammer probes and insulated deep probes to provide both surface and core readings; both the moisture content and approximate depth should be recorded.

9. Where moisture content readings exceed 20%, action points should be agreed including mitigation measures to limit further wetting where possible, and a strategy for implementing drying measures, particularly where non-breathable insulation products and construction details have been specified.

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10. Remedial drying regimes should consider time taken for the recorded moisture contents to dry at various conditions; BM TRADA and Stora Enso can provide further information on likely drying times based on moisture content, depth and anticipated temperature and relative humidity. Forced/accelerated drying should consider the risk of forcing water in the upper wet face of the panel further down. Where the second and third laminations are at a low moisture content, trading some of water in the first lamination into these may be acceptable. However, causing the lower laminations to exceed 20% moisture content should be avoided. Ideally, where heat is being used to speed up drying, it should be applied evenly to both sides of the panels.

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Acknowledgement

We would like to thank Stora Enso for funding and supporting this research work. We would like to specifically thank Jennifer Eriksson from Stora Enso for her input into this research and her assistance in preparing this summary report.

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