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Built-in moisture in cross-laminated timber roofs – a field study

J E Gaarder[1] and T D Pettersen[2]

[1] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway
[2] Construction Products Norway (Byggevareindustrien), and the board of Roof Producers Research Group (TPF), 7186 Oslo, Norway

jorn.e.gaarder@ntnu.no

Abstract. Cross-Laminated Timber (CLT) elements have had a growing popularity in recent years due to i.e. low carbon footprint, low weight and efficient construction time. However, the elements are sensitive to moisture and prone to organic growth if not treated properly or if used incorrectly. Roof slabs are particularly exposed, as they have a large area of exposure and the horizontal orientation doesn't allow rainwater run-off. The efforts made to protect CLT-roofing elements by Norwegian contractors vary widely, as there are few guidelines and little long-term experience. A field study of CLT-roofs on existing buildings was conducted to investigate the conditions after some years in service. The study includes inspection and moisture measurements of CLT elements from the exterior side in 10 building projects 1-9 years old from two regions of Norway. The contractor of each project was interviewed in order to assess the extent of climate exposure and protection measures during construction. The results indicate a correlation between water content, building age and exposure level during construction. There is a clear indication that the drying time for built-in moisture in CLT roof constructions are slow. Keeping built-in moisture to a minimum is therefore paramount.

1. Introduction

1.1. Background and objective

The use of Cross-Laminated Timber (CLT) elements in the Norwegian building industry has become increasingly popular in recent years due to i.e. low carbon footprint, low weight, and efficient construction time. However, the elements are sensitive to moisture and prone to organic growth if not treated properly or if used incorrectly. The widespread use of CLT-elements is relatively new in Norway, and studies have shown that there is a demand for clear and updated guidelines for using CLT-elements [1].

After the structural CLT shell is in place at a building site, it stands exposed to the elements for a period before the weather screen is in place, and moisture uptake from rain may accumulate if the CLT are not temporarily protected in some way. Roof slabs are particularly exposed, as they have a large area of exposure and the horizontal orientation doesn't allow rainwater run-off. The efforts made to protect CLT-roof elements by Norwegian contractors vary widely, as there are few guidelines and little experience with potential consequences over time. A method for creating CLT Construction Guidelines involving the construction industry is demonstrated by Wahlstrøm [2], but the guidelines are not yet completed.

The dry out rate of built in moisture in this type of system needs investigation, as this is an important parameter for deciding the level of moisture protection measures needed in the building phase. The objective of this study is to map the conditions and water contents of existing compact CLT-roofs, to answer the following research questions:

- What measures are taken during construction to reduce the rain exposure of CLT-elements in compact roofs in Norway?
- What effect do the protection measures have on the built-in moisture levels, and how is the dry out capability of the built-in moisture over time?

1.2. Climate strains

The Norwegian climate puts great demands on the moisture resilience of buildings. Moisture related damages are the most prevalent damages of Norwegian buildings [3], and moisture uptake in the building phase is one of the problems in general [4], and for CLT-roof elements in particular [1]. Wooden materials are highly responsive material with regards to moisture, and roofs may be exposed to precipitation in the period between instalment of the CLT-elements and instalment of the water-proofing membrane.

Climate change leads to higher levels of precipitation in most parts of Norway, and more importantly it leads to higher precipitation intensities. In addition, the temperature rise will result in more winter precipitation falling as rain and better growth conditions for mold- and rot fungi [5]. Combined, these factors constitute greater climatic strains and higher risk of moisture related damages for Norwegian buildings, particularly for wooden constructions.

1.3. Hygroscopic properties of wood

Dry wood has a relatively high diffusion resistance, which means that a dry CLT-element can be utilised as a vapor barrier, given sufficient thickness. Laboratory testing of the diffusion resistance of CLT-elements made of spruce at different moisture levels have shown that an element thickness of 100 mm at 15-18 %-mass water content have an Sd-value of approximately 2-3 m [6]. Since the diffusion resistance of wood varies with the water content, this complicates matters when assessing the dry-out capability of a CLT-element under a compact roof. With or without vapor barrier on top, the principal transport way of built-in moisture in a compact CLT-roof is through the underside of the element. As the moisture near the lower surface dries out, the diffusion resistance will increase, and reduce the dry-out rate of the remaining moisture. This can be a serious problem if the CLT element is exposed to precipitation during the construction phase, as the wettest part will have the longest transport way.

The climate in Norway is such that the outside temperature is lower than the indoor temperature for most parts of the year. This means that the temperature gradient over the CLT-element will be mostly such that the moisture will need to be transported towards the warmest parts of the element, contrary to the natural direction for temperature induced free moisture transport.

2. Methods

2.1. General

We have conducted water content measurements of 17 compact CLT-roof segments on 13 different buildings from 8 different projects in the middle and eastern parts of Norway. One roof segment is defined here as a separate, enclosed level of a building’s top surface. The roofs have been installed by 6 different contractors for 3 different building owners. The measurements were conducted over three periods, in November 2019, April-June 2020 and October 2020. After each field study, the contractors were interviewed in order to assess climatic exposure and protective measures during the building phase.

2.2. Field measurements

The measurements were conducted from the outside, and the contractor that installed the roof were responsible for opening and closing the construction before and after the measurements. Each roof segment was opened at 1-3 different measurement points, most often 2; one near the drain (where the insulation thickness is thinnest) and one near the edge (where the insulation thickness is thickest). For each measurement point, the following procedure was followed. 1. Visual inspection of the insulation, exposed CLT-surface and vapor barrier for signs of ongoing or dried out water damages, 2. Water content measurements of the CLT-element at 0-2 mm, 20 mm and 40 mm depth, using an electric resistance meter, and 3. Repeating the measurement 5-15 cm from the first in order to reduce measurement uncertainty. The moisture measurements were calibrated with regards to temperature, using thermoelements at approximately 30 mm depth and at the surface level.

2.3. Moisture meter

An FME moisture meter produced by Broikhus was used to measure the water contents. Two pointed electrodes, insulated such that only the tip is conducting electricity and spaced apart, is driven into the wood in order to measure the electric resistance of the material. The electric resistance of timber will vary with water content, temperature and material density. When calibrated for density and temperature, the moisture meter will calculate the water content of the wood based on the electric resistance between the electrodes.

The moisture meter is pre-calibrated for a measurement area of 7-27 %-mass water content. Assuming correct calibration of temperature and density, the measurement precision is 0,5-2 %-mass water content, with lower water contents giving better precision.

2.4. Interviews

In addition to the moisture measurements, informal interviews with the contractor and the operations manager for the building was conducted to collect information about the conditions during the building phase as well as any possible problems during the operation phase. In addition to the interviews, a document study of the project documents was conducted where available.

3. Results

3.1. Visual inspection

None of the inspected positions revealed visible signs of mould growth or rot decay. However, a number of the positions showed cracks between the lamellas in the CLT-element, which indicate higher moisture levels and subsequent drying out. Studies have shown that extensive mould growth may be present even without visual signs [7], however due to the scope of the study no laboratory measurements of mould growth have been conducted.

The solution choices varied to some extent between the inspected roofs. 7 out of 17 inspected roof segments had PE-foil as a vapor barrier between the CLT-element and insulation layer. 8 out of 17 used an asphalt-based membrane as a provisional, temporary roofing to protect the CLT-elements during the building phase, which also functions as a vapor barrier during the operations phase. 2 out of 17 roof segments had a vapor open membrane between the CLT-elements and the insulation layer. All but one of the buildings used mineral wool as insulation material, and all but one used an asphalt-based membrane as roofing material.

3.2. Measurement results

The results from the field measurements are presented in Table 1 and **Figure 1**. Measurement series 111 through 322 was conducted in November 2019, series 411 through 512 in June-September 2020, and series 611 through 831 in November 2020. The water content measurements are given as an average of 0-2 mm, 20 mm and 40 mm depth measures. The water content as a function of depth showed a slight tendency to be higher for the winter measurements and a slight tendency to be lower for the summer measurements. The variations in depth due to seasonal variations in temperature is in line with findings from other studies of moisture profiles in a drying or wetting conditions ([8] [9]).

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Table 1. Summary of measurement results

Measurement number[a]	Building age	Measurement at 0-2 mm depth (%-mass)	Measurement at 20 mm depth (%-mass)	Measurement at 40 mm depth (%-mass)	Average	Type of barrier between CLT and insulation
111	< 1 year	14,7	16,6	16,5	15,9	Provisional roofing
112	< 1 year	16,5	18,1	18,0	17,6	Provisional roofing
121	< 1 year	13,6	15,4	15,7	14,9	Provisional roofing
122	< 1 year	13,0	13,6	15,8	14,1	Provisional roofing
211	9 years	8,1	8,0	8,1	8,0	Provisional roofing
212	9 years	6,8	7,0	7,0	6,9	Provisional roofing
311	3 years	12,1	11,5	11,9	11,8	Diff. open barrier
312	3 years	9,5	9,2	8,9	9,2	Diff. open barrier
321	3 years	9,8	10,6	10,2	10,2	Diff. open barrier
322	3 years	9,8	10,1	10,1	10,0	Diff. open barrier
411	2 years	15,3	15,4	15,4	15,3	Vapor barrier
412	2 years	16,3	15,4	16,8	16,2	Vapor barrier
421	2 years	12,9	13,0	13,2	13,0	Provisional roofing
422	2 years	21,7	19,7	19,6	20,3	Vapor barrier
511	2 years	16,0	15,4	15,4	15,6	Vapor barrier
512	2 years	15,1	13,9	12,9	13,9	Vapor barrier
611	7 years	10,0	10,8	11,0	10,6	Vapor barrier
621	7 years	10,9	11,3	11,6	11,2	Vapor barrier
631	6 years	9,0	9,2	9,5	9,2	Vapor barrier
641	6 years	9,5	11,1	11,0	10,5	Vapor barrier
711	5 years	10,6	10,9	10,5	10,7	Provisional roofing
712	5 years	10,8	10,8	11,0	10,9	Provisional roofing
721	5 years	11,3	11,6	11,7	11,5	Provisional roofing
722	5 years	12,8	12,8	13,8	13,1	Provisional roofing
811	2 years	10,4	11,9	11,5	11,3	Provisional roofing
812	2 years	10,3	11,5	11,7	11,2	Provisional roofing
821	2 years	14,4	15,7	15,5	15,2	Provisional roofing
822	2 years	8,0	9,0	9,0	8,7	Provisional roofing
831	2 years	12,1	no measure[b]	no measure[b]	12,1	Provisional roofing

[a]The first digit denotes the building project number, the second digit denotes the roof segment number and the third digit denotes the measurement number on the designated roof segment.
[b]No valid measure obtained, due to low battery on the moisture meter

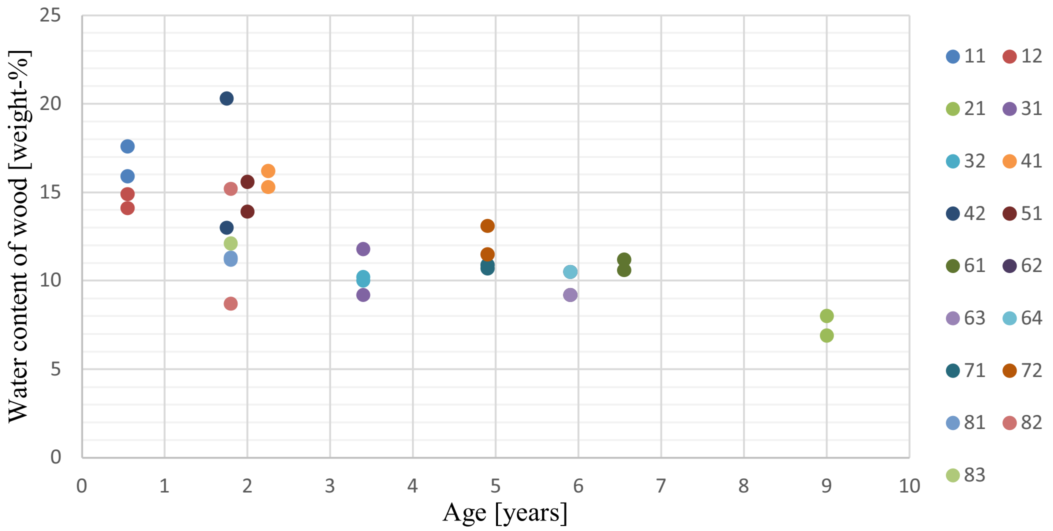

Figure 1. Measurement results of each roof segment, showing the relationship between water content of CLT-elements and age of the building. Roof segments are separated by colour. Legend digit 1 denotes the building project number, and digit 2 denotes the roof segment number.

3.3. Interviews and document studies

The informal interviews of the contractors and document study of relevant project material provided by the contractors, such as emails, progress reports, quality assurance documentation etc, provided insight into the weather conditions during construction and the implemented protection measures to reduce rain exposure.

Table 2. Results from interviews and documentation study, showing the relationship between rain exposure, protective measures and measured moisture levels in the CLT-elements. Since the building ages varies, difference in water content within a single roof segment is used as an indicator of high built-in moisture levels, rather than the absolute water content (assuming that high exposure leads to varied water content in the CLT-element as the first area to be covered will be exposed to less rain).

Building number[a]	Period between CLT installation and roofing[b]	Total rain exposure between CLT installation and roofing[c]	Reactive protective measures to reduce built-in moisture[d]	Maximum difference of water content within one roof segment (%-mass)
1	Short	High		1,6
2	Short	High	Yes	1,1
3a		High		2,6
3b				0,2
4		High		7,3
5		High		1,7
6a			Yes	0,6
6b			Yes	0,6
6c		High	Yes	1,3
6d		High	Yes	1,3
7a	Short		Yes	0,2
7b	Short	High	Yes	1,6
8		High		6,5

[a]For projects involving multiple stages (constructing multiple buildings), the stages are separated by lettering
[b]Denoted as **short** where roof-over-roof was used or provisional roofing was installed within a week of CLT-element instalment.
[c]Denoted as **high** where either the interviews and documentation study gave indications that rain exposure was a problem during

construction or the roof was exposed over a long period (weeks or months).
[d]Denoted as **yes** where the contractor either actively dried out the elements or allowed for natural drying through delayed construction, or when water content measurements were used actively as a quality assurance measure.

There were 6 contractors in total, constructing 13 different buildings on 8 different projects (some projects had multiple stages) spanning from 1 to 9 years old. For this reason, the data quality varies greatly between the different roof constructions, so we were not able to pinpoint exact dates for the different construction stages through the documentation study. On the other hand, we collected a rich anecdotal data collection on the weather conditions and protection measures implemented through the interviews, giving good indications on the exposure levels for the CLT-elements. The data collected is therefore qualitative and subjective in nature, and the uncertainties only allow for a rough estimation of rain exposure and protective measures implemented. The results are summarized in Table 2.

4. Discussion

4.1. Relative water content as an indicator of high exposure

Note that since the buildings are of different ages, direct comparison of absolute water content between the CLT-elements of the different roofs cannot be made for other purposes than to show the relationship between water content and age. For this reason, an assumption is made that the relative difference in water content within a single roof segment implies exposure to rain during construction. Water content for different areas on a roof will vary when rain exposure time vary, since typically the roof instalments in this study took several weeks to complete. Roof segment 42 (see Table 1) illustrates the theory elegantly. For some reason only half of this roof was covered with provisional roofing, and the exposure time for the other half was at least one month longer. The provisionally covered part of the roof had an average water content of 13,0 %-mass and the exposed part had an average water content of 20,3 mass-%. Since no other differences between the roofs were found, this implies that rain exposure time is the reason for the difference in water content. Thus, an assumption is made that higher exposure to rain leads to larger differences in water content within a roof segment. Note that there could be other reasons for differences in water content in general, i.e. different indoor climates and damages to the membrane, but on the buildings in question no such differences were found. Further, the differences in water content for different areas on the same roof segment will probably be reduced as the building gets older, as higher water contents probably dry out faster. This effect has been ignored in this study, as the potential difference in dry-out time is unknown and quite difficult to estimate.

4.2. Reduction of built-in moisture in CLT-elements

The relationship between exposure level, type of measures taken and built-in moisture reported in Table 2 deserves further discussion. The results are summarised into two categories in Table 3 below; either high exposure level or not, and differentiated on type of measures taken by the contractor during construction of the roof.

Table 3. Difference in %-mass water content within one roof segment, as a function of exposure to rain and protective measures taken by the contractor.

Rain exposure level	Proactive measures	Reactive measures	No measures
High exposure	1,4	1,3	4,5
Low exposure	0,2	0,5[a]	0,2

[a]reactive measures for low rain exposure include measurements of water content before roofing, as a quality assurance.

Proactive measures include either instalment of provisional roofing within a week of CLT-element instalment or building under roof-over-roof, and reactive measures include efforts to reduce the water content of the CLT-elements after rain exposure and before roofing as well as water content measurements before roofing in some cases. When categorizing the data in this fashion, two clear tendencies emerge. The first concerns the exposure level, namely that higher exposure levels correlate with higher relative differences in water content within a single roof segment, as discussed in chapter 4.2.

The second tendency is that both proactive and reactive measures reduce the built-in moisture considerably compared to no measures at all, when rain exposure is high. Admittedly, the sample pool is somewhat small, however there are 4 cases reported to have high exposure to rain in combination with no special efforts to cover or dry out the CLT-elements, and these 4 cases also have the 4 largest differences in water content within one roof segment. The findings in this study, regarding moisture protection measures, are analogous to the results found in the literature: it is clear that a strategy for reducing the risk of built-in moisture is important for CLT-construction [10-12].

4.3. Dry-out capability of CLT-elements in compact roofs

Comparing the measured water content of the CLT-elements and the age of the building, as in **Figure 1**, the trend is that older buildings have dryer CLT-elements. Both the absolute water content and the relative difference in water content within a roof segment are smaller for the older cases, both good indicators that the built-in moisture of a CLT-element under a compact roof will dry out through the inner surface over time. But if this trend is representative, it shows that the dry-out time is quite large, and most practically measured in number of years. This is due to the vapor barrier preventing dry-out on the top surface, and the thickness of the element preventing dry-out through diffusion. Other studies of dry-out capabilities of CLT found similar results, high moisture contents dry out relatively quickly but dry-out rate decrease rapidly as moisture content is reduced towards equilibrium with ambient conditions [13]. The cases are not differentiated by thickness of the CLT-elements, but all the known thicknesses are within the range of 150-200 mm. A linear regression of al the cases gives a dry-out capability of approximately 1 %-mass water per year, but the dry-out speed will probably vary with the water content, and as such the water content over time will not follow a linear curve.

5. Conclusions

The following conclusions are made based on the results from the field study:

- Built-in moisture in compact roofs with CLT-elements will dry out inwards over time, although drying-out time can take many years before reaching equilibrium. There were no observable signs of mould- or rot-growth in any of the exposed elements, but cracking was a relatively common phenomenon.
- Proactive measures to reduce built-in moisture, such as fast built times and quick covering of the CLT-elements by provisional roofing leads to reduced differences in measured water content within the same roof segment, given high rain exposure. Efforts to dry out the rainwater that penetrated the CLT-elements after a rain event also gave the same result. High rain exposure without either proactive or reactive measures gives the opposite result. The choice of strategy between proactive and reactive measures is an economical consideration, as proactive measures leads to certain higher costs and reactive measures leads to a risk of even higher cost due to delays.
- When rain exposure is low, the differences in measured water content within the same roof segment was low, and proactive measures had no significant effect. This supports the assumption that large differences in measured water content is a sign of high water uptake from rain water during the construction phase. Roof segment case number 42, with a 7,3 %-mass water content difference between two points, is a clear example of the effect, as half of the roof was covered with provisional roofing and the other half was exposed for multiple weeks.

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