

Observations of Moisture Damages in Historic and Modern Wooden Constructions

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Abstract. *With the introduction of new building products made of planar glued board lamellas, the CLT, the restriction of load-bearing structures to linear and thus additively used load-bearing members was abolished. As a result, new, technically determined boundary conditions for moisture management in the interior of buildings have arisen. Due to the emergence of massive, planar wall and floor components as in concrete construction, the integration of building services technology in timber construction must now take place differently than was traditionally the case. In addition, it can be observed that the damage to building components is increasing, the detection of moisture damage is becoming more difficult and, ultimately, the consequences and risks are not yet foreseeable. The study focuses on the cause-effect relationship of increased water input and uses selected examples to reveal the problem of moisture exposure in the interior of buildings with planar load-bearing structures, the damage mechanisms and direct consequences set in motion. This paper shows the necessity for moisture protection measures in modern timber structures in comparison to traditional ways to construct with timber. It shows where moisture intake with modern structures must be considered and avoided from the engineering perspective in order to minimize the risk of moisture damage.*

Keywords: *Moisture Damage, Mass Timber Construction, CLT, Damage Mechanisms, Durability, Risk.*

1 Introduction

Wood is one of the oldest construction materials in our history. Due to its one-dimensional growth direction, it is mainly found in one-dimensional, linear components. This fact has significantly influenced the building with wood in the last centuries. Individual beams were used for load transfer, which worked alone or in combination with other beams. Only in the last decades a new building product has arisen by the emergence of the adhesive technology, which has created the breakthrough into our construction everyday life under the name *CLT*. In recent years, *CLT* has become one of the most popular building products for engineering timber construction. From today's point of view, its origins go back a very long way. In Central Europe, the first nailed *CLT* elements from the beginning of the 20th century are known under the name of construction method *Broda* (Kersten, 1926). In 1929 (Pohl, 1934), the Building Research Institute in Moscow had extensive investigations carried out on cylindrical shells made of nailed *CLT*. It was not until many years later (1992) that the company *Holzbau Merk, Aichach*, Germany, gained experience in the production of glued, large-format elements from crossed board lamellas. On this basis, the first general building authority approval (AbZ Z-9.1-354) was issued in 1998 under the name *Merk Dickholz*. Since this time, *CLT* production has shown a steady increase in production. According to the internet news portal *Holzkurier*, an annual

production output of 1.2 million cubic metres of cross-laminated timber is to be achieved in 2020 (Ebner, 2017).

The development of the cross-laminated timber construction product has massively changed the way walls and floor are designed. The once linear components of timber construction (beams) are increasingly being replaced by planar components made of cross-laminated timber. Construction times and construction heights can be reduced by constructing on the plane (see Figure 1), as the plane that encloses the room is combined with the load-bearing layer. The closed plane, which is formed by cross-laminated timber, is not only advantageous. If a building is to be constructed, different types of construction can be used for building floor. From a structural engineering point of view, the bending stiffness of the type of construction used is usually decisive, since it characterizes the serviceability limit state. If a 4-metre *CLT* floor is compared with a wooden beam floor, it can be seen that the *CLT* floor requires only 2/3 of the construction height of the beam floor with the same bending stiffness, cp. Figure 1.

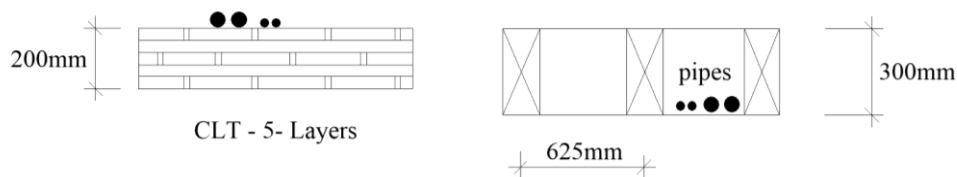


Figure 1. The two main different types of timber floor systems, a *CLT* plate with 2-axial structural span (left) and a traditional framed floor of joists with a 1-axial span (right). The installation of water pipes with respect of the type of construction is shown.

This article is intended to examine the problems of flat components with regard to their moisture resistance, special damage mechanisms as well as their causes and effects and the risks of repair, and to point out possible problem solutions and approaches for practical implementation.

Moisture damage generally poses a major problem in the construction industry and for wood components made of the renewable building material wood as well as most wood-based materials. Humidity usually does not destroy the building material suddenly, but slowly and gradually. What is the reason for this? On the one hand, wood itself has good resistance to short-term exposure to moisture. If the material can dry off quickly and the water content falls below 18% by mass again, then there are no concerns about durability. Even changing moisture contents of the material are in themselves harmless, although there are geometric changes in the cross-section due to shrinkage and swelling during moisture supply or removal. The geometrical changes are not to be classified as harmful if there are sufficient degrees of freedom of the component or a subcomponent. This shows examples, like wooden roof shingles from larch wood, which are to be found for example in the Alpine region frequently. Despite their constantly changing moisture content and additional exposure to wind and solar radiation, both of which promote drying, the material has a service life of 30 years or more in this application field.

In the case of moisture damage in the construction industry, most damage to wood only comes to light after a long period of time, apart from large and sudden damage events such as defects in water pipes. This type of defect is either concealed and is not noticed by anyone or the amount of moisture is small but constant and the damage mechanisms set in motion work slowly.

Damage mechanisms in wood and wood-based materials can be divided as follows: phenomena and damage mechanisms that do not damage the structure, directly damage the structure and indirectly damage it. Non-structural damaging mechanisms include the formation of mould on the material or component surface and blue stain fungi. These can be listed, however, as healthwise precarious and optically aesthetic lacks. The wood-destructive fungi (brown rot, dry rot) belong to the second damage-mechanism that leads to irreparable structure-damages in the material due to continuous high humidity. The last group of indirect damage mechanisms is triggered by moisture-dependent shrinkage and swelling and the reduction in strength due to high moisture. These two characteristics do not initially lead to damage to the material. However, shrinkage and swelling can lead to cracks in the cross-section along fibres and cause damage to entire components or adjacent components due to deformation of the cross-section, as the change in moisture can lead to large forces in the material. This can be observed in connection with internal stresses or settlement of components, but does not necessarily lead to damage to the material itself. By reducing the strength due to high humidity, deformations of the load-bearing component due to forces are possible and thus damage to the load-bearing or adjacent components is possible. The systematics of the damage mechanisms and their consequences are described in detail by (Ott *et al.*, 2017) in the report of TallFacades. The research project focused on moisture damage in the building envelope and the effects of weather and climate. It was already recognised that there are major risks of moisture damage inside buildings. The generally applicable damage mechanisms are not discussed in detail, nor are the direct consequences, since both can be read in the above-mentioned report on TallFacades. In principle, they also do not change in the event of damage inside buildings. In this article we get to the bottom of the following questions, following the damage and searching for the causal chain that leads to damp damage inside the building:

- i) Which damage events can be observed inside buildings and how can the indirect consequences be linked with the overarching consequences of moisture damage?
- ii) Which components are affected by moisture impacts and where have the damage mechanisms affected to what extent over time?
- iii) How does the causal chain of damage mechanisms for the specific impact work?
- iv) How much water and moisture has affected the wood.
- v) Where does the impact (triggering event) come from?

Are there indications somewhere in the causal chain, either in the type of action or in the damage mechanisms or at the end in the direct and indirect consequences, which in particular are related to the aforementioned planar *CLT* structures?

In the discussion and summary, hints are given for the avoidance of impacts, elimination of damage mechanisms and minimization of consequences for the respective construction method (planar or linear). In addition, supplementary measures for the protection of the construction against excessive and continuous exposure to moisture are proposed through regular monitoring. Their final areas of application and application procedures, the testing and control of success are described in detail in a further paper.

2 Methods

2.1 Data

In order to analyse the relationships between the damage mechanisms and impacts, data from several damage surveys and expert opinions of the last five years are evaluated and compiled in Table 1. Specific information is taken from the sources in order to identify and further classify the damage to the construction methods and components.

Table 1. Data from evaluated multi-storey and mid-rise timber buildings.

Building and use	i) Construction type	ii) Structural part with damage	iii) Damage mechanism	iv) Water amount	v) Source of water
hotel	flat, 2-axial floor slab	top side <i>CLT</i> slab	top layers rotten	bathroom, leaking pipe	water on floor, below screed, not detectable
school	flat roof as warm roof, and beam structure	roof panelling, on bottom & top of beams	wood panels (OSB), rotten	construction moisture, no drying	tight roof top, vapour tight interior layer,
new office on top of existing parking, depot and heating plant	extension on RC-structure flat roof: beam flooring with timberframed panels	insulation inbetween beams, panelling	wet cellulose ins., beams, sills, and rotten panelling	construction moisture, high convective moisture input	neighbouring glass house, missing vapor barrier floor and edges, open shafts
daycare for children	nail laminated elements	nail laminated floor slabs and wall panels (1 st floor and roof)	swelling of lamellas of elements, damage of connected elements	construction moisture, rain, high amount	missing protection during construction
pv-installation on tilted roof	beam structure	insulation inbetween beams, panelling	beams wet and dark coloured, wood panels rotten	rain water and convective moisture	small holes in roof cladding, penetration by pv-fixation

2.2 Procedure of Case Studies Analysis

The causal chain of the damage event and the damage mechanism, according to (Tietze et al. 2016), is evaluated and structured on the basis of the descriptions from the expert opinions and their categorization in Table 1. The following procedure is used: the primary influence of water damage on the position and size of the damage to the component is analyzed by the mutual investigation of the effect on the component and the damage resulting in the component. Information is evaluated to answer i) the general question about the occurrence of moisture damage in multi-story wooden buildings and ii) about the construction method and the affected

areas in the building components. The respective damage mechanism and the causal chain leading to the damage are determined in question iii) on the basis of the categorization of the damage patterns or according to the type of damage to the component. The trigger of too much moisture in the component is presented in question iv) according to the quantity and duration of the water impact. Finally, v) investigates the cause of excessive moisture ingress which leads to corresponding damage.

2.3 Systematization Results Case Studies

The systematization of damage mechanisms and their consequences is described in detail in the final report of the research project TallFacades (ibid.). The generally valid damage mechanisms are not discussed in detail, neither are the direct consequences, since both can be read in the report on TallFacades. In TallFacades the focus of the investigation was on moisture damage in the building envelope and the effects of the weather as a major cause and it has already been recognized in TallFacades that there are major risks for moisture damage inside buildings. These were only cursorily surveyed and the specific damage mechanisms were not dealt with either. As with the damage in the building envelope, the nature of the specific effects on internal components and the resulting indirect consequences in the building are explained in more detail. From this, initial findings on typical damage events will be summarized.

3 Results

3.1. Damage Incidents Inside

The evaluation of the results from the investigated case studies produces the following impact categories: Category of the size of the moisture input over time and the cause of the moisture input. The extracted subcategories are further specified in the explanations in the unexpected events in the interior of the building, mostly of great magnitude, which can be traced back to technical systems and which are paired with constructive characteristics. The primary damage mechanism is capillary water absorption. Another mechanism to be observed is the convective moisture input through unsealed components such as shafts or floor levels between different areas of use. The diffusive moisture input is hardly relevant. In addition, the loss of insulation properties and thus a building up effect of the humidity is not to be recognized in the present cases and unlikely, since the constructions lie predominantly in the interior and insulations are not necessary. With the few construction elements to the outside climate these are either completely unsealed or they show holes, which make the penetration of liquid water possible, which represents an unacceptable deficiency from the outset.

3.2 Construction Status (t=0)

As described in Chapter 1, *CLT* floors are becoming more and more popular as lower construction heights are required compared to beam floor with identical bending stiffness. However, with *CLT* floors, it is not possible to easily distort installations at the structural level. These must be installed in separate levels either above or below the *CLT* floor. This is different for beam floors, where pipes can also be routed between the beams, see Figure 1.

3.2 Unplanned Event = Damage (t=1 ... n)

Moisture damage is one of the most frequent types of damage in residential buildings. These are often caused by leaking pipes or design faults. In beam floor, the escaping water often migrates through the construction level and escapes at the underside and thus becomes visible quite quickly. Furthermore, the water inlet and outlet areas of beam floors are usually close to each other. If water is exposed to a closed surface such as *CLT*, the water moves to the deepest point of the structure where it collects, see Figure 2. Since the surface is usually closed and the water cannot pass unhindered through the construction level, it sometimes remains lying there for a long time and searches its way downwards along paths that are sometimes difficult to follow. Thus the place of the moisture entry and the place of the exit may be far apart. Furthermore, it can take a very long time until such moisture damage is detected. As an example the *CLT* floor of a hotel is shown here, where a damaged water connection was not found over 8 years, see Figure 3. From the once 220 mm thick *CLT* floor 100 mm have been decomposed by wood-destroying fungi. The floor structures originally did not suggest any damage, as the top of the floor and the underside of the floor were dry. In addition, the location of the maximum damage was several meters away from the cause of the damage (leaky water connection). Due to the very low construction height, the renovation was very costly. Auxiliary steel structures have to be used to replace the damaged *CLT* elements with new ones and to support the roof structure above.

Table 2. Categories of exposure and related reasons.

Scale & Time category	Reason	Explanation
large & suddenly	pipe burst, household appliance burst, sprinkler	- (unexpected event)
small & long-term (water source related)	pipe and fitting leakage, pipe connections	material damage, (quality management)
	complex and integrated installations	water leakage not detectable, continuous water supply (leakage)
small & long-term (construction technology related)	type of structures in mid-rise housing	large areas with flat slabs, thick slab dimensions, seldom beam structures
	ducts crossing different units without necessary barriers (air stops)	missing awareness & planning, expensive task, complex on-site work, no quality management, difficult maintenance
	type of indoor climate conditions	warm, humid, no or limited air- flow, no dry-out capacity

4 Discussion

4.1 Construction Technology Overview

The danger of moisture damage occurs wherever liquids are transported through pipe systems. Therefore, it is important to consider how structural measures can look like in order to avoid moisture damage as far as possible or to detect it as early as possible. If possible, pipes should be routed in such a way that they can be inspected. In addition, particularly vulnerable areas of

buildings such as wet rooms (bathrooms, toilets, washrooms, kitchens) should have special sealing systems that draw the user's attention to moisture damage and, for example, have overflows.

4.2 Outlook Repair ($t=m$)

If damage to the load-bearing structure is known, it must be repaired. In the case of the beam floor, the repair of damaged beams is relatively simple. In the simplest case, the damaged beams can be removed and replaced. Alternatively there are possibilities of lateral reinforcement by additional beams, construction materials or steel. As there is still space between the beams, this can be used for repair purposes. This is different for *CLT* constructions. Since the construction space is already completely occupied, *CLT* cannot simply be renovated or reinforced on the existing level. If a *CLT* floor cannot simply be replaced, complex constructions are often required to carry out the renovation. This is also reflected in the repair costs.

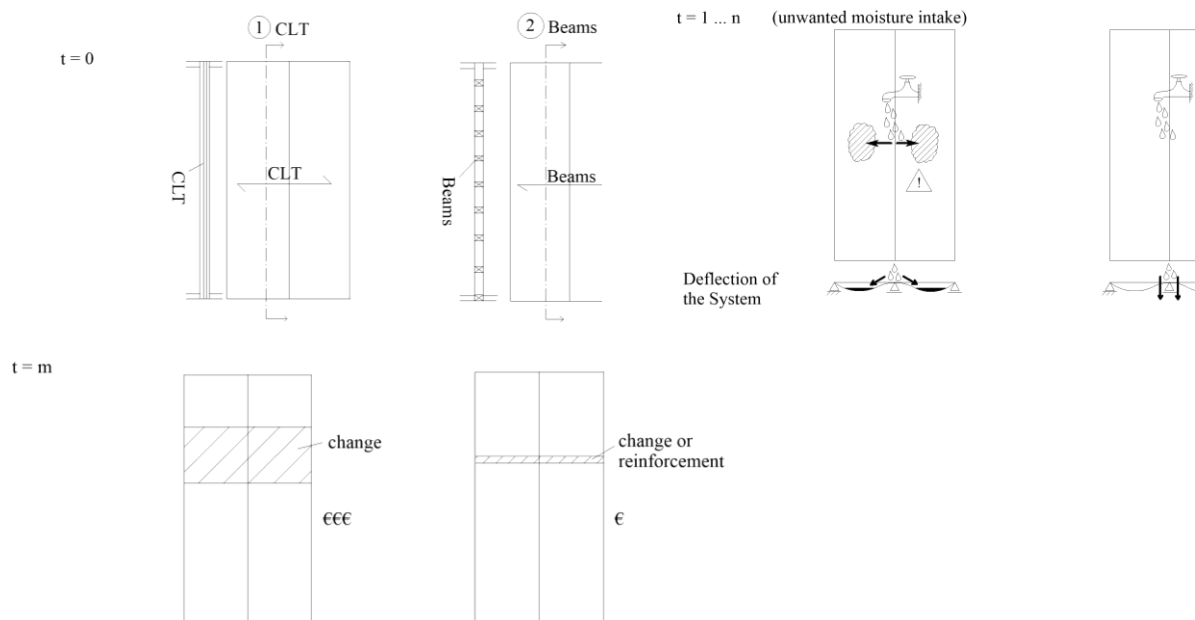


Figure 2. Timber floor systems 2-axial (left column) versus 1-axial during assembly $t = 0$, $t = 1 \dots n$ with moisture intake and finally $t = m$ with possible repair scenarios.

4.3 Outlook Monitoring

Since moisture leads to large damages in floor systems as discussed above, it is possible to set up appropriate monitoring systems. These can, for example, record the amount of water fed into and discharged from a building or room and issue a warning if the difference is too large. On the other hand, humidity sensors can also be installed directly at critical points. These humidity sensors would be particularly suitable for *CLT* floors, where water can wander along and is only discovered very late. This can be done by sensors placed close to the surface or in the wood.

5 Conclusion

The conclusions can be summarized as follows:

- Moisture damage with related wood decay inside buildings is a relevant problem,
- Such damages are difficult to detect because the damage mechanisms are acting slowly,
- Massive, planar structural components are particularly affected by slow decay mechanisms,
- Wood decay effects are mainly occurring due to defective water pipes on top of the floor.

In principle, the earlier an unexpected moisture penetration in timber constructions is detected, the smaller the damage and the lower the cost of restoration measures



Figure 3. Pictures of damaged CLT slab and wall elements in hotel room.

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