A Visual Assessment of Cross-laminated Timber Structures in Austria

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Abstract

Cross-laminated timber (CLT) construction systems have been used commercially for over 20 years, mainly in Western Europe and North America. However, there has not been a report on the current status of CLT buildings. Deterioration of wooden buildings could result from a variety of causes, and the life of the structures could be extended if periodic inspections were conducted. This research introduces a visual inspection methodology for assessing deterioration of CLT structures. The inspection methodology was tested in six CLT buildings in Austria. The methodology was proven to be effective in determining the current internal and external condition of the examined CLT structures. The oldest CLT structure inspected dates from 2004. The newest structure inspected was still under construction. The results of the application of the visual inspecting tool show that there was very little damage to the CLT structures. Visual inspections cannot always find damage to structural members, but it is an accepted inspection methodology to discover potential causes or more severe damage. The main causes of damage came from exposure to water on the exterior of the buildings and poor control of humidity and temperature in indoor conditions. Architects who designed the inspected buildings were interviewed to cross validate the results of the visual inspection methodology. In addition, the interviews provided important insights related to the design, construction, and current conditions of the buildings. Furthermore, the architects also provided information regarding the main barriers and drivers that affect CLT construction in Austria.

Keywords: cross-laminated timber, CLT, inspection tools, wooden buildings, inspection, wood deterioration

1. Introduction

Cross-laminated timber (CLT) construction systems started in Germany and Austria at the end of the 1990s. In less than 20 years, this construction system has become very popular in Western Europe and in North America (Karacabeyli & Douglas 2013, Muszyński 2015, Pei et al. 2016, Harte 2017). Private and public organizations in these regions are leading the effort in sustainable construction around the globe, and CLT construction systems are perhaps the best way to achieve their goal of decreasing the carbon footprint in the construction industry, by sequestering carbon in the thick wooden walls, floors, and roofs.

There has not yet been research showing results of the status and longer-term durability of CLT buildings. The first CLT structures are now over 20 years old, and there are questions about their current status and potential damage from fire, weather, fungi, or insects. Most of the CLT members in buildings in Europe and North America are not exposed to direct moisture from rain. In addition, a variety of solutions have been implemented to allow for quick removal of moisture, such as better ventilation systems and using air circulation to remove water from structures.

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Architects, who are interested in using renewable materials for their projects, see CLT systems as a great way to mitigate the carbon footprint in construction systems and also as a strategy to increase aesthetic beauty, while decreasing lead times and overall manufacturing and construction costs (Viļuma & Bratuškins 2016). Companies that have participated in CLT construction projects have indicated that these systems can decrease their construction lead times by 25% or more, compared to other materials, impacting overall construction costs (ThinkWood 2020).

This project addresses the lack of an available tool or method to evaluate the performance of CLT buildings using visual criteria. Therefore, the project seeks to answer the following research question:

What criteria could be used to assess the performance of CLT buildings using visual methods?

To answer this question, a visual deterioration inspection tool for CLT structures was developed and applied to CLT buildings in Austria. The inspection methodology included an assessment of the buildings' performance related to moisture, insects, fungi, sunlight, and occupancy. In addition to the visual inspection, interviews with the occupants, the architects who designed the buildings, and the builders themselves were conducted to complement the visual inspections and to determine the perceptions and realities of the design and construction of CLT buildings.

2. Background Research

Cross-laminated timber is an engineered wood panel that is composed of an odd number of layers of lumber, which are arranged with the grain directions oriented at a 90-degree angle to each other and connected by adhesive bonding. This engineered wood product was developed in Germany and Austria. Production of CLT panels in Europe is expected to reach 1.2 million m^3 by 2020 (Ebner 2017).

Just as any other structure, deterioration in wood buildings may result from a variety of causes during the life of the structure, and periodic inspections are critical to detect deteriorated material that needs to be repaired or replaced (Highley 1999, White & Ross 2014). Wood-decay fungi decompose the wood cell wall and require a relatively high moisture content (MC) in the wood, typically near or above 30% MC. Many wood-boring insects prefer wood with high MC, but some insects, such as powder post beetles and old house borers, can live in relatively dry wood with MCs as low as 10%. A properly constructed wooden building in the temperate climates of the world will have interior MCs between 6% and 10%, and protected exterior wood may have MCs in the range of 12% to 16% (Simpson & TenWolde 1999, Loferski 1997). Wood will decay if it is in a situation that causes the MC to raise to the 30% level, which may be caused by contact with moist ground or exposure to water from different sources, such as rain, plumbing leaks, or condensation (Loferski 1997). In addition, drier wood is less likely to be attacked by insects.

Visual inspection of all types of buildings is very common in the construction industry; for example, Delgado et al. (2013) developed an inspection and diagnosis protocol for wood flooring systems. The authors developed a list of defects, including surface, aesthetic, functional, and joints and interfaces. The defects are visually inspected using an urgency repair classification, where 0 means immediate action, 1 means action required within 12 months, and 2 means action required in the long term. The protocol also correlates defects with potential causes. Researchers have developed a methodology for the visual inspection of selected engineered wood products and connector hardware for prescriptive non-compliance at the pre-drywall stage of residential construction (Bouldin 2011, Bouldin et al. 2013, Loferski et al. 2013). The researchers indicated that there was no standardized inspection methodology, but options were available, such as the top-down method and sighting along the patterns of repetitious framing elements to detect defects or non-compliant installations. In addition, Bouldin et al. (2014) conducted similar research to visually inspect the installation of trusses in residential construction with the goal of detecting truss installation errors.

Onsite inspection of wood members is often limited by the capacity of obtaining sufficient information (Saporiti et al. 2019). There are cases where the research/inspection team has plenty of time and resources to conduct the inspection and more data is collected. For example, Russell et al. (2006) conducted an assessment of a 15-year-old stress-laminated timber bridge in Augusta, GA, USA. The team conducted the following tests: moisture tests in wood members, re-stressing of post-tensioning bars, photo documentation of bridge site, load test with deflection and longitudinal strain measurements, and in situ vibration testing. Levi (1975) suggested a procedure for the inspection of residential buildings outside and inside that involved visual detection to look for excessive moisture around the house.

Lately, there has been a trend in architecture to consider wood as a viable option for large structures. However, there are still factors or barriers that prevent the use of wood as a permanent, long-lived construction material. Espinoza et al. (2016) investigated potential barriers for CLT adoption by surveying timber engineering and civil engineers with a focus on wood construction in Europe. It was found that compatibility with building codes, availability of technical information, misperceptions about wood or CLT, and cost were the most significant barriers noted by these experts in Europe. Similar results were obtained by Viļuma & Bratuškins (2016) in their study conducted in Latvia which surveyed 73 architects and asked them about barriers preventing the use of wood in construction projects. The most significant barriers in decreasing order of importance were stereotypes, legislation, specialist qualification, lack of knowledge, lack of experience, lack of information, and inaccessible consultancy.

3. Methods

A visual inspection methodology was developed as a checklist to evaluate the condition of CLT buildings. The inspection methodology was applied to six buildings in Austria in 2019. The inspection methodology was based on the experience of the authors and literature such as Levi (1975), Loferski & Espinoza (2014), and the USDA Forest Service (1973). The tool included three sections: a general description of the building, an evaluation of the exterior, and an evaluation of the interior.

The general building description section included 10 items: location, inspection date, date of construction, number of stories, area of the building, CLT panel manufacturer and builder, architectural firm, type of construction, type of finishing, and a sketch of the building.

Table 1 shows the items to be inspected on the exterior of the building. A rating scale of 0, 1, or 2 was assigned to each item. A rating scale value of "0" meant "not evident"; a value of "1" was given for "some evidence"; and scale value of "2" was assigned for situations with "very evident" features. These scale ratings were also used

Table 1. Items to be inspected on the exterior of the building.

#	Evidence of deterioration	0	1	2	Comment (location of damage, etc.)
1	CLT panels exposed to rain (presence of overhangs, etc.)				
2	CLT panels exposed to condensation (windows and doors)				
3	Exposure to runaway water from rainwater				
4	Untreated structural wood is below 8 inches from the ground				
5	Lack of siding (lumber, shingle, panel, others)				
6	Direct contact of CLT panels with soil				
7	Decay signs in architectural rain run-off areas such as doors, windows, balconies				
8	Decay in water trapping joints (panel edges)				
9	Evidence of shrinkage and swelling				
10	Lack of flashing				
11	Presence of blue stain				
12	Presence of surface black staining (such as mold or mildew)				
13	Presence of fungi or rot				
14	Water damage in concrete foundation (splash wetting)				
15	Damage caused by UV light				
16	Insect damage (termites and borers)				
17	Presence of carpenter ants and bees				
18	Deterioration of CLT panels in contact areas with concrete				
19	Visible damage on glue lines				
20	Deterioration of CLT panels in contact areas with steel				
21	Signs of mechanical wear				

Damage scale: Not evident (0), Some evidence (1), Very evident (2).

to indicate the presence, or absence, of deterioration in the building. An overall building rating was calculated by averaging the individual ratings.

The interior of the building was evaluated using the checklist shown in Table 2. A rating scale similar to the exterior parts of the building was used to evaluate each item or feature of the building interior.

Case study methodology was used to collect the data for the validation of the inspecting tool. First, appointments with the building managers and architects of the selected buildings to be inspected were set up between February and May 2019. The list of buildings to be inspected is shown in Table 3. The real names of the buildings and architects were removed to preserve the confidentiality of the research. Note that architect 1 designed buildings A, C, and D. The inspection of the buildings was conducted in May 2019.

Second, the research team prepared a questionnaire for the building occupants and the building managers to obtain additional information in support of the inspection tool. The questions for the building dwellers included aspects related to the living and working conditions offered by the structure, such as noises, interior temperatures, and smells. Also, a question about reported complaints or damage to the structure was included. For the building managers, the authors included questions

Table 2. Items to be inspected in the interior of the building.

#	Evidence of deterioration	0	1	2	Comments
1	CLT panels exposed to natural elements				
2	CLT panels exposed to condensation				
3	Lack of finishing (plain, varnish, stain, paint, etc.)				
4	Decay signs in architectural rain run-off areas such as doors, windows, balconies				
5	Evidence of shrinkage and swelling				
6	Lack of flashing				
7	Presence of surface black or grey staining (such as mold or mildew)				
8	Presence of fungi or rot				
9	Insect damage (termites and borers)				
10	Presence of insects (carpenter ants and bees, etc.)				
11	Deterioration of CLT in contact areas with concrete				
12	Visible damage on glue lines				
13	Deterioration of CLT in contact areas with steel				
14	Signs of mechanical wear (walls and flooring)				
15	Visible water leaks				

Rating scale: No evidence (0), Some evidence (1), Very evident (2).

Table 3. Characteristics of buildings to be inspected.

Building name	Architect	Construction type	Year of construction	Area (m^2)
A	1	Prefabricated walls, CLT system for ceiling/floor	2004	4,500
B	2	CLT system for walls and ceiling/flooring Concrete core	2012	1,700
C	1	Prefabricated CLT dormitories	2014	8,000
D	1	CLT system for walls and ceiling/flooring Concrete core	2014	1,200
E	3	CLT system for walls and ceiling/flooring Concrete core	2016	126
F	4	CLT system for walls and ceiling/flooring Concrete core	2019	600

regarding building inspection procedures, maintenance, and issues with the building such as noises, deterioration, energy consumption, and overall performance.

A set of questions was also formulated to the architects who designed the structures. The topics in this set of questions included: the decision process for selecting CLT for the structure, major challenges before and during the construction of the building, cost of the project, references to similar projects completed by the architects, and feedback from the building dwellers or building managers.

4. Results and Discussion

4.1 Visual inspection of the buildings and interviews with dwellers and building managers

Building inspections and interviews of architects took 5 days. Table 3 shows the characteristics of the buildings that were inspected. The oldest structure was low-income housing, built in 2004. Building F was still under construction when inspected, but even though it was new, the inspection of this site provided critical insights into construction methods, building codes, and potential early damage to the structures.

Building A: Residential

This project was designed by architect 1 and built in 2004. The project features three buildings, each with 60 flats and total area of 4,500 m^2. The project was developed to provide social housing for people in Salzburg, Austria. The walls of the building were prefabricated and included structural insulated panels (SIP). CLT panels were used only in the ceiling and flooring systems. The exterior walls included insulation and exterior siding made of larch lumber. A space of 3 cm was left between the siding and the exterior water-resistive membrane for air circulation to allow for quick removal of moisture.

A relatively small amount of deterioration was observed due to green staining in some parts of the siding on the exterior parts of the buildings. The siding showed heavy discoloration due to exposure to ultraviolet light (see Figure 1). The siding was close to the ground and did not have protective flashing to avoid rain splash contacting the siding.

These buildings were inspected from the exterior only. Discussions with architect 1 indicated that, initially, there was a concern regarding the long-term maintenance and upkeep because the buildings were intended for social housing, but it seems that the tenants had taken good care of their housing units. Interviews with the buildings' occupants were not conducted, but according to architect 1, "the tenants love their building." In addition to the architectural features and overall design of the building, the tenants also enjoyed the low maintenance costs of the building.

Figure 1. Direct exposure to sunlight and moisture accumulation on siding leading to (a) discoloration and (b) blue, black, or green staining.

The overall grade for this building was 0.33 in 0-2 scale, where 0 is no damage evident and a score of 2 means damage is very evident.

Building B: Commercial

The building was designed by architect 2 and built in 2012. It is considered a commercial building, has three stories, and an area of 1,700 m^2. CLT panels were used for the walls and the ceiling/floor system. The CLT wall panels were exposed in the interior, but on the outside the panels were covered with insulation, and there is gap between the wood siding and the insulation for air circulation.

According to the architect who designed the building, the cost of using concrete vs. wood was similar, but the customer decided to use CTL panels because the customer wanted to have better living conditions in the building. It took over a year to complete the project. The building has been recognized by the construction and architectural community and has received design prizes.

The wood siding showed sunlight damage and gray or black staining. The inspection did not find any evidence of decay on the exterior side of the CLT walls, but evidence of water damage was found in the balconies. Figure 2a shows discoloration that was visible on the exterior and interior surfaces of the siding and CLT panels, especially beneath the balconies. The water damage found in the balconies could have been prevented by adding appropriate flashing, to minimize water penetration into the end grain of the wood in the CLT panels. Figure 2b also shows some delamination of the interior CLT panels, likely caused by cyclic changes in the humidity of the internal environment of the building.

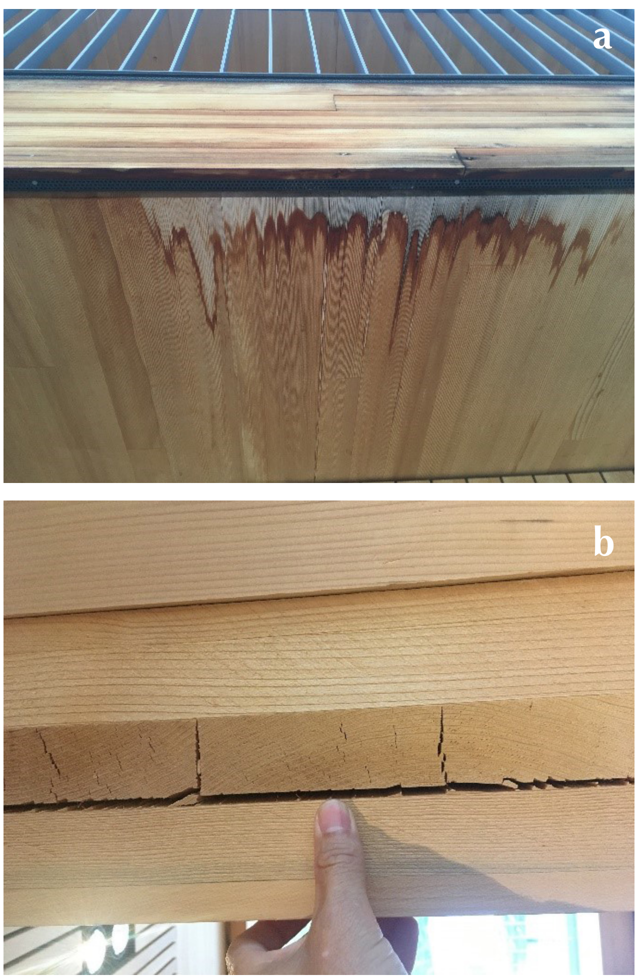

Figure 2. (a) Exterior signs of discoloration in the CLT balcony; (b) interior checking of CLT panels.

The tenants of building B were pleased with the overall performance of the structure. The building is 7 years old, and there have not been any major structural or serviceability issues. The building is very quiet and pleasant, but the tenants reported that it tended to get very hot in summer because the large glass windows collected the warmth of the sun. This could be causing low relative humidity in the interior, leading to delamination and wood splitting, as seen in Figure 2b.

Based on visual inspection, this building received a 0.30 on a scale from 0 to 2.

Building C: Residential

This building was designed by architect 1 and built in 2014. The structure features five stories, 136 bedrooms, and an area of 8,000 m^2. An innovation was that each bedroom was a self-contained box unit, which was prefabricated off-site, using CLT panels. The boxes were brought to the construction site and stacked on top of each other to assemble the building, a modular system. The building has a concrete core in the middle for the elevator shafts, and the first floor is made of concrete. The siding of the building is made of copper.

The exterior of the building was inspected and did not show any visual signs of decay or related problems, as expected, but there was evidence of water infiltration near the windows, which could cause wood decay in the future.

The interior of the building had evidence of shrinkage and swelling of the wood. There were gaps between panels, splits in the CLT surfaces, and gaps near the openings around windows, doors, and walls. These issues were likely caused by the accumulated shrinkage and swelling of the overall system. The architect pointed out that the structural integrity of the building was not compromised.

The issues were more evident in the upper floors, as the impact of the movement of wood, due to the absorption and release of moisture, accumulated. The image in Figure 3a shows a black cell phone inserted into a 12 mm gap between a door frame and the ceiling. Figure 3b shows a pronounced wave in the surface of the floor system.

According to the building manager, the tenants liked living in the building. The manager also reported that the main issue was the expansion of the wood in the

Figure 3. (a) A gap between a door and the ceiling; (b) ceiling and floor showing waving in the fifth floor due to the impact of accumulated shrinkage and swelling of CLT boxes.

vertical direction, which was magnified by the height of the fourth floor. This caused some visible gaps, and interference, and binding when closing and opening doors.

The overall grade for this building was 0.82 on a scale of 0 to 2.

Building D: Commercial

This building was built in 2014. It has three stories and is 1,200 m^2 in area. The structure was awarded a wood building construction award in 2019. CLT panels were used for the walls and the floor/ceiling system. The panels were classified as industry grade by the CLT manufacturer. The exterior of the building had wood shingles for siding made from larch species. The building had a core concrete structure to meet fire prevention regulations. The stairs were made of concrete and were attached to the core concrete structure. The exterior of the building had little to no deterioration, except for water damage in the balconies or overhangs (see Figure 4a). The wood siding covered and protected the CLT walls from the direct wetting from rain. The CLT walls were exposed in the interior, but water-resistive material was applied on the exterior of the CLT panels. There was a gap between the wood siding and the insulation to allow for air circulation and quick removal of moisture.

Inside the building there was some visible damage related to changes in moisture content of the building interior. Splitting and separation of the CLT lamellas was noticeable (see Figure 4b) in several sections of the ceiling/flooring CLT panel system. The CLT panels were fabricated by gluing only the face side of the lamellas and not the edge.

The overall grade for this building was 0.84 on a scale of 0 to 2.

Figure 4. (a) Damage caused by exposure to moisture into the end grain of the CLT panels near the bottom of the overhangs; (b) splits in the surfaces of the CLT panels caused by changes in equilibrium moisture content inside the building.

Building E: Residential

This is a private home with an area of 126 m^2 and three stories. The structure was built in 2017 and took about 7 months to complete. The owner and designer of the house is architect 3, who has been involved with CLT construction systems since the year 2000. Architect 3 pointed out that the most critical aspect, when constructing with CLT panel, is protecting the structure from moisture. Air circulation is critical to remove undesired moisture from the interior and exterior of the structure.

In this structure, CTL panels were used for the walls and the ceiling/floor system. Similar to the previous structures, the wall CLT panels were exposed in the interior of the structure. Insulation and siding were added on the exterior side of the walls. The siding was made of spruce boards and was painted to slow water penetration and potential attacks from insects and fungi. The exterior inspection did not reveal any particular issues with damage or decay.

Steel beams were used to support the CLT ceiling/floor system. The only visible defects in the interior of the house were some delamination and splitting in the wall CLT panel, which is considered normal.

The inspection grade for this project was 0.75 on a scale of 0 to 2.

Building F: Residential

This project was still under construction when the visit was conducted. The company completed a similar project adjacent to the new construction, which was already occupied by tenants.

The area of the new project is 600 m^2 for eight flats on three stories. CLT panels were used for the wall and the ceiling/floor systems. The project included underground parking and a concrete elevator shaft. Figure 5 shows a view of the exterior, still under construction.

The thickness of the CLT panels used in the floor system was 24 cm. All ducts for utilities were run on top of the floor CLT panels. A 20 cm layer of lightweight concrete was poured on top of the utilities to cover and protect them. Additionally, the concrete layer contributed to noise abatement and to strengthen the floor structure (see Figure 6a).

The internal CLT walls were covered with gypsum wallboard in most of zones. The architect decided not to have the CLT wall panels exposed. This was a visual and aesthetic decision. The gypsum wall coverings can be seen in Figure 6a. Insulation was added to the external face of the wall CLT panels, as shown in Figure 6b. The insulation was painted after installation to prevent or slow down potential damage from exposure to water.

The balconies were part of the ceiling/floor structure. Flashing material was used to protect the CLT panels from water and moisture, as shown in Figure 7a. However, some signs of staining were visible, as seen in in Figure 7b.

Figure 5. Exterior view of apartment complex, Building F.

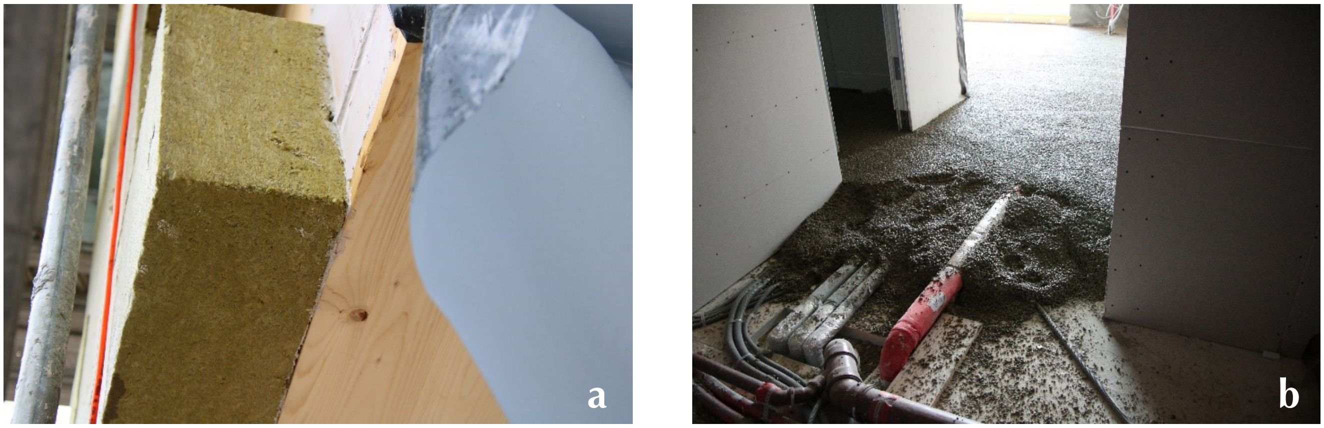

Figure 6. (a) Light-weight concrete being poured on the CLT floor system; (b) insulation added to the exterior CLT wall.

Figure 7. (a) Flashing used in balconies; (b) visible damage caused by water exposure in balconies.

Even though this project is still under construction, there were no signs or evidence of damage in the structure. It seems that the construction techniques being used will enhance the durability and performance of the CLT systems.

Tenants who were living in the adjacent apartment complex indicated that they were very happy with their building. Tenants liked the climate control system because the building features passive heating and cooling systems. Occupants also indicated that they liked the smell of wood and the sustainability and environmental aspects of the building.

The overall grade for this project was 0.24 on a scale of 0 to 2.

Table 4 summarizes the assessment of the six buildings that were inspected. In all cases, there were no visually identifiable issues compromising the structural integrity of the buildings. The bigger issues arise from changes in humidity in the internal conditions of the building and the damage from exposure to water and sunlight on the exterior of the buildings.

4.2 Interviews with architects

The architects involved in five of the six CLT projects presented in this paper were interviewed in order to clarify and obtain additional information after applying the visual inspection tools. There were three projects designed by architect 1: buildings A, C, and D. Buildings B and E were designed by architects 2 and 3, respectively. The research team was not able to interview the architect who designed building F, but instead interviewed the developer of this building. See Table 5 for details.

The architects agreed that the architect, planner, and contractor must work closely together to make sure the project goes well. This input aligns with the findings by Muszyński et al. (2017). Project lead times varied from project to project, but there seemed to be agreement among the architects that it could be from 6 to 12 months. For example, a single-family house could take from 5 to 7 months. The developer for building F indicated that a 600 m^2 apartment complex with eight flats took about 10 months to complete. The use of

Table 4. Summary of the inspection procedures.

Building Code	Rating (0-2)	Major issues found
A	0.33	Presence of black, gray or green stains in the exterior of the building.
B	0.30	Sunlight damage and black and gray stains, water damage in the end grain of the balconies. Delamination in the interior CLT panels.
C	0.82	Evidence of water infiltration near the window. In the interior, evidence of shrinkage and swelling (gaps and splits).
D	0.84	Water damage in balconies and overhangs. Visible damage in the interior caused by changes in moisture content.
E	0.75	Visible delamination and splitting in the interior but considered normal.
F	0.24	Early signs of water damage in the exterior (black stain) were visible.

Table 5. Data from the architects and building contractor interviewed.

Architect	Year of first CLT project	CLT projects per year	Major challenge	Major driver
1	2002	5-8	Static loading, evaporation, and acoustics	Wood creates better living and learning conditions
2	2001	3-4	Planning between architect, CLT manufacturer, and contractor	Government regulators more receptive to timber construction
3	2000	10-15	Requires more up-front planning than other construction systems	Customers want to see more wood
Developer	2014	2nd CLT project	Acoustics abatement	Sustainability and environmental aspects of wood

wood for construction in Austria has grown from a 3% to 30% market share over the last 20 years. This increase in the use of wood, and specifically CLT construction systems, has put a lot of pressure on CLT manufacturers, and construction lead times are increasing. The inspection of the buildings did not show any damage related to over-exposure of the panels to inclement weather conditions during construction. The observation of the construction of building F showed that there is a high level of coordination between the architect, the CLT manufacturer, and the construction company to expedite the construction process. A big challenge with CLT construction is keeping the panels dry during inclement weather, and the panels must be handled with special care to avoid contact with water or excessive exposure to sunlight during construction.

The architects indicated that fire risk concerns are still a critical barrier that must be overcome for each project. In many cases, code officials are not very familiar with CLT construction systems, and architects need to work with code officials to get all the permits aligned and authorized. Architect 1 indicated that younger code officials tend to be more receptive to CLT construction systems than are older ones. This input from the architects regarding fire performance should be considered in the visual inspection tool.

The architects also agreed that the overall project costs are similar to concrete and steel. Most customers believed that building with the CLT systems was more expensive than using concrete and steel, so the architects needed to spend time with customers to explain that costs were indeed similar. However, the developer of building F indicated that CLT construction systems are still more expensive than standard concrete construction because CLT systems are relatively new and, for some contractors, are more difficult to use than standard systems.

During the inspection of the buildings, building managers and dwellers interviewed indicated a high level of satisfaction with the performance of the buildings related to sustainability and social aspects. These types of aspects were not included in the visual inspection tool, however, because they are difficult to evaluate by sight alone, without asking people who interact with the buildings. Both managers and dwellers recognize that a CLT structure could be more expensive than a concrete or steel building, but both groups pointed out that sustainability aspects such as better insulation, carbon sequestration, and the use of renewable materials are equally or more important than just the cost of the building. Socially speaking, dwellers love the wood surfaces in walls, ceilings, and floorings. Similar results were found by Conroy et al. (2019).

When building with CLT systems, the architects agreed that the designer must have excellent knowledge of wood mechanics, wood connections, techniques to keep water and moisture away from wood, and vibration and noise abatement systems, in addition to understanding the structural design of buildings. One architect indicated a preference for exposing the exterior face of the CLT panel for aesthetics and not using moisture barriers or coatings on the exterior CLT panel face. During the application of the visual inspection tools, it was found that all the buildings were designed following the basic principles to prevent moisture presence in exterior and interior surfaces. With a couple of exceptions, damage due to exposure to moisture was observed, but this damage in those cases was not compromising the structural integrity of the building. It is important to note that the critical aspects related to the design of this type of building were included in the visual inspection tool.

The interviewees indicated that the main advantages for CLT customers were a great living atmosphere, sustainable construction, and short construction lead time. According to the contractor of building F wood gains and releases moisture in the atmosphere, which creates better living conditions for occupants. The interviewees indicated that wood creates better living and learning conditions. The indoor working environment is becoming more important in the decision process of selecting a construction material for a building. This seems aligned with recent research by Kotradyova et al. (2019), where their study highlights the positive impact of wood environments for humans.

5. Conclusions

A visual inspection tool to evaluate the interior and exterior damage of CLT structures was successfully developed and implemented in six CLT buildings in Austria. The application of the inspection tool was complemented through interviews with the building managers, dwellers, and the architects who designed the buildings.

The CLT buildings that were inspected in Austria have design features that protect the CLT panels from weather. All of the inspected buildings showed little or no evidence of decay or insect damage. Most of the observed decay was found in the wood shingles used for siding, which can be easily replaced without impacting the performance or integrity of the building.

In regards to the construction techniques used in the inspected buildings, it was found that common construction techniques for CLT floor systems in Austria use a layer of lightweight concrete on top of the CLT floor system to increase acoustic performance of the building. Architects also indicated that CLT construction systems require more planning from architects and contractors than other standard construction systems. In addition, both architects and contractors still have concerns about fire codes.

Regarding the level of exposure of CLT panels, wall CLT panels are usually exposed in the interior of buildings and insulation and siding are added to the external side of the CLT panel to protect against weather (rain and sunlight). It seems that the exposure of CLT panels in the interior of the building is an attractive feature for customers because of perceived environmental benefits, and the building environment provides excellent living and working conditions.

The interviews with building dwellers, managers, and architects during visits to the buildings were very useful to validate and complement the findings from the visual inspection. This tool was designed to work as a stand-alone visual inspection protocol, but open questions were introduced in order to determine if the tool had missing elements, conflicts, repetition, or implementation issues. It was found that the visual tool should have included an item to evaluate aspects related to fire performance and also items to evaluate the social and environmental performance of the building. In addition, the questions to the dwellers and building managers were important to determine the overall satisfaction with the building, something that can only determined by asking people. Overall, the visual inspection tool was found to be useful in determining the general exterior and interior conditions and the acceptance and performance of the inspected CLT buildings.

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