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RESEARCH ON THE DURABILITY OF ORTHOGONAL GLUED CROSS-LAMINATED TIMBER UNDER GROUND CONDITIONS

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ABSTRACT: Industrially, cross-laminated timber (CLT) has become a popular building material because it is environmentally friendly, looks good and is easy to install. CLT is made up of 30mm thick sheets of wood called laminations. CLT is manufactured by gluing the lamellas together in the direction of the fibers, orthogonally to each other. Since its invention in Europe in the 1990s, the use of CLT has grown worldwide, gaining popularity for its potential in architectural and civil engineering applications, including soil stabilization and paving. As CLT is primarily composed of wood, its use will play a significant role in meeting the 2050 global carbon neutral targets. However, the use of CLT in civil engineering is hampered by a lack of awareness of how long CLT will last in different climatic conditions. Compared to its use in buildings, where it remains mostly in an air environment, CLT for civil engineering is often exposed to soil, water and fluctuating climatic conditions. This study examines the degradation characteristics of CLT under geotechnical conditions by investigating its material integrity and mechanical properties under varying exposure conditions. A series of visual inspections revealed that the lamina delaminated and cracked under long-term exposure regardless of climatic conditions and installation orientation, and furthermore, climate-dependent deterioration, such as feeding damage by termites, was observed. Mechanical testing revealed a proportional loss of strength over the course of the two-year exposure, confirming the vulnerability of CLT to geotechnical applications with increasing time. Despite these observations, the study is limited by the two year exposure period and future long-term studies are required to assess the feasibility of CLT for longer term civil engineering applications. This study highlights the importance of continuous monitoring and optimization of CLT durability to realize its full potential in infrastructure development.

KEYWORDS: cross-laminated timber, durability, wood protection, mass timber, civil engineering

1 – INTRODUCTION

Cross-Laminated Timber (CLT) is a very prestigious structural material due to its eco-friendliness, aesthetics, and ease of installation. CLT is made from 30 mm-thick boards of wood, known as lamina, glued together with their fiber orientations at right angles to one another. This structure surpasses strength anisotropy, a common weakness of wood, thereby enhancing its mechanical behavior and making it suitable for application in civil engineering construction projects that require high resistance. In addition, with a unit volume weight approximately one-fifth that of concrete, CLT enables easier construction, shorter project timelines, and enhanced transportation efficiency. With such advantages, CLT has excellent potential for application in civil engineering. In Japan, the initiatives of utilizing wood in infrastructure development align with the world's objective of achieving carbon neutrality by 2050 (Fig.1). Wood is an environmentally friendly alternative to fossil fuel-based materials due to its capacity to lock up carbon for long periods and its relatively low energy consumption during production. CLT is a relatively new product in this segment, and its utilization is expected to increase. In the US, a prototype highway road soundproofing wall was tried out to check the degradation in its performance upon exposure to moisture, apart from its structural integrity, cost, and durability. Results indicated that CLT soundproof walls, if duly treated to withstand moisture, would be viable alternatives to precast concrete barriers [1].

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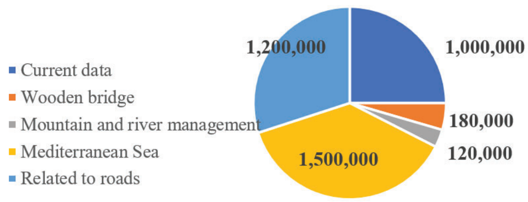

Figure 1. Potential for wood use in the civil engineering field in Japan, assuming an annual wood use of 40,000 m³ [2]

Although there is a wealth of durability information on CLT in aerial exposures, such as soundproof walls, underground exposure is more challenging [1]. With the potential of CLT as a structural material, its application can be extended to paving slabs and ground reinforcement, where conventional materials such as cement and steel are the standard. In underground applications, research has suggested the durability of logs in soft ground construction projects [3]. Although abundant durability data are available for CLT under aerial conditions [4] [5], systematic and comprehensive studies on its durability under underground, underwater, and near-ground conditions are not yet available. This kind of knowledge gap is one of the significant barriers to the widespread application of CLT in civil engineering.

Recognizing the lack of durability data for CLT in ground conditions, ongoing research in Japan is investigating its performance in ground reinforcement technologies [6]. While insightful information regarding durability can be obtained from traditional wood piles, CLT's adhesive layers and panelized nature are different enough to necessitate specialized research. Exposure testing under geotechnical conditions was conducted in this study to assess the structural integrity and strength properties of CLT. Samples were put into place in conditions that mimicked the field, with baseline performance measurements taken before placement. One-year (2022) and two-year (2023) strength tests and surface observations were conducted to measure how the properties of CLT changed over time. By closely matching the conditions of actual application environments, quantifiable durability information gained in this research provides the basis for long-term performance estimation of CLT, thus paving the way for its quick integration into civil engineering applications.

2 – SUMMARY OF EXPOSURE TESTS

2.1 TEST CONTENTS AND METHODS

To investigate the effects of air and soil exposure conditions on the strength and soundness properties of Cross-Laminated Timber (CLT), exposure tests were conducted by exposing CLT block specimens in different places with different temperatures and amounts of precipitation. The CLT samples used in the exposure tests were shaped into 150 mm × 150 mm × 150 mm blocks. The specimens were constructed from 30-mm laminae, which were piled alternately in an orthogonal manner, to create a 5-layer × 5-ply configuration (Fig.2, Photo 1).

Figure 2. Photo1. Shape of CLT specimens used in exposure tests

Native Japanese softwood species Japanese cedar (*Cryptomeria japonica D. Don*,) was selected for the layers of all laminae. It was selected due to its classification as a medium-level decay-resistant species as rated from field pile tests—a universally accepted method of assessing wood resistance to decay under natural environmental conditions (Table 1). Incorporation of a moderately decay-resistant species was intended to act as a control level of performance against biological degradation.

Table 1: Decay resistance levels by species in the field pile tests

Decay resistance level	Years of service	Japanese softwoods	Japanese hardwoods	Foreign timber
High	7-8.5 years in the field	・Japanese cypress（*Chamaecyparis obtusa*）	・Japanese zelkova (*species of elm-like tree , Zelkowa serrata*) ・Japanese chestnut (*Castanea crenata*)	・Port Orford cedar（*Cupressus lawsoniana*） ・Yellow cedar (*Chamaecyparis nootkatensis*)
Medium	6-6.5 years in the field	・**<u>Japanese cedar (*Cryptomeria japonica*)</u>** ・Japanese larch (*Larix leptolepis*)	・Japanese oak (Quercus robur) ・Mountain cherry（*Prunus Sargentii ssp. Jamasakura*）	・ Douglas fir (*Pseudotsuga menziesii*)：trees found in mountain forests
Low	3-4.5 years in the field	・Fir（*Abies firma*） ・Red pine（*Pinus densiflora*）	–	・Western hemlock（*Tsuga heterophylla*） ・Douglas fir (*Pseudotsuga menziesii*)：trees that inhabit riverside areas other than mountain forests
〈OPEN-AIR TEST〉 ・Piles of 30 x 30 x 600 (mm) were made from wood, buried halfway in the soil, and periodically removed for observation. ・The piles were periodically pulled out and observed. The sound condition with no damage was classified as level 0, and the completely collapsed condition as level 5. ・The number of years elapsed when the value reaches 2.5 is certified as the service life of the species (wood).				

The Japanese cedar (*Cryptomeria japonica D. Don*,) orthogonally laminated board strength grade was Mx60-5-5, as specified in the Japanese Agricultural Standard (JAS). In this grading designation, Mx refers to different grade configurations, whereas the strength grade (average bending modulus) of the outermost laminae is 6.0 GPa (Table 2).

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Table 2: Strength performance of CLT of Mx60-5-5 strength grade (Japanese Agricultural Standard: JAS)

Strength grade	Configuration classification	Bending Young's modulus		Bending strength
	Consists of different grades	average	Lower limit value	
		Gpa,10^3N/mm^2		Mpa,N/mm^2
Mx-60-5-5	5 layers,5ply	4.2	3.4	9.8

Two types of adhesives were used to laminate the laminae in the lamination direction: resorcinol-formaldehyde (RF) and water-based polymer isocyanate (API). They are both common adhesives for controlled laminate timber (CLT) production. However, no adhesive was applied on the side edges of the laminae for free expansion and contraction. Because the CLT samples were made for use in ground conditions, no preservative treatment such as pressurized chemical impregnation was conducted to prevent likely environmental influences.

2.2 ESTABLISHMENT OF FLUCTUATION FACTORS

There were five variation parameters established for this study to examine the strength and soundness properties of CLT under the air and soil exposure conditions (Table 3).

Table 3: Variation conditions in exposure tests

Variable conditions	Parameters set
Exposure years	0/1/2 years (plan to follow up after 3 years)
CLT adhesive	Resorcinol resin-based adhesive(RF)/ Water-based polymer isocyanate adhesive(API)
Climate	Subarctic/ Temperate/ Subtropical
Installation location	GL+0.5m(in air)/ GL±0m(at ground level)/ GL-0.25m(in ground)/ GL-0.5m(in ground)/ GL-1.5m(in ground)

Adhesives type was a variation parameter of the utmost significance in this study. Whereas glued laminated timber (glulam) has enjoyed an extensive history of application, having been in widespread application in the United States since the 1930s and in Japan since the 1950s, CLT remains a relatively new product. Various adhesives, such as casein, urea-formaldehyde (UF), resorcinol-formaldehyde (RF), melamine-urea-formaldehyde (MUF), and water-based polymer isocyanate (API), have been used traditionally for engineered wood products. Nevertheless, there remains limited long-term durability information for CLT. Therefore, RF and API, the two most common adhesives in current CLT production, were selected as variable factors.

The Japanese Agricultural Standard (JAS) prescribes CLT manufacturing specifications and stipulates suitable adhesives based on intended service conditions. API, having lower water resistance than RF, is only approved for indoor use within controlled environments. RF, however, has higher resistance to weathering, heat, moisture, and fire. JAS classifies three service conditions:

Use Environment A: Highest resistance to weather, heat, moisture, and fire.

Use Environment B: Same fire resistance as Environment A but with lower weather, heat, and moisture resistance requirements.

Use Environment C: Same weather, heat, and moisture resistance as Environment B, but without requirements for fire resistance.

Although with less water resistance, API was also rendered a variable in this study since it has a smaller environmental impact. Compared with solvent-based RF that contains formaldehyde, API is a formaldehyde-free water-based adhesive and thus a more environmentally friendly adhesive. The decay of wood is influenced by biological in addition to physical factors. Biological breakdown consists of fungal decay and insect damage, while physical breakdown is caused by exposure to sunlight, heat, rain, wear, wind, and mechanical stress. Climatic conditions directly influence physical degradation and indirectly impact insect and fungal attack. Previous research on the most suitable conditions for the growth of 22 strains of basidiomycetes, which cause wood decay in structures such as bridges and house foundations, indicated that medium to high temperatures are conducive to fungal growth [7]. Similarly, adhesive degradation is influenced by environmental conditions. Chemical degradation can result from exposure to heat, moisture, light, and chemicals, and physical degradation can result from fatigue and thermal cycling, and creep. Climatic conditions thus influence the chemical and physical degradation of adhesives. In view of these considerations, climatic conditions were introduced as a significant variable in this study. The geographic diversity of Japan offers a range of climatic conditions, and three test sites were selected to represent different climate zones. Based on W.P. Köppen's five types of climate [8], test sites in the subarctic and temperate zones were considered(Table 4).

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Table 4: Three Japanese cities where exposure tests were conducted

Climate Zone	City Name
Subarctic	Asahikawa City, Hokkaido
Temperate	Miyoshi City, Hiroshima Prefecture
Subtropical	Miyakonojo City, Miyazaki Prefecture

Among temperate climate subtypes (warm humid climate [Cfa], summer monsoon climate [Cwa], and Mediterranean climate [Csa]), those with the highest mean summer temperature were selected first. The tropic al, arid, and polar climates were not taken into consideration. Table 5 shows the climatic differences in temperature, humidity, sunshine, and rainfall that are considered to be related to deterioration in the three regions.

Table 5: Climate observation data by climate condition

Climate Zone	Temperature (℃)					
	Average of 1 month		Monthly average of the highest temperature of the day		The monthly average of the minimum temperature for one day	
	min.	max.	min.	max.	min.	max.
Subarctic	-8.3	24.6	-4.2	29.9	-12.9	20.4
Temperate	2.1	27.6	7.4	33.6	-1.5	23.6
Subtropical	6.4	27.5	13.2	32.2	0.7	24.3

Climate Zone	Relative humidity (%)				Sunshine hours (h)		Precipitation (mm)	
	Average of one month		Minimum humidity of one month				Total for one month	
	min.	max.	min.	max.	min.	max.	min.	max.
Subarctic	65	86	10	54	38.5	228.3	46	180
Temperate	76	87	24	38	90.3	193.4	24	262.5
Subtropical	73	86	11	44	107.6	216.8	54	823

Samples were positioned at varying depths about the ground level to simulate different exposure conditions: (Fig.3,4) (photo2,3)

GL + 0.5 m: Above ground, fully exposed to air,

GL ± 0 m: Exposure at surface level

GL - 0.25 m, -0.5 m, -1.5 m: Completely buried beneath the ground at varying depths.

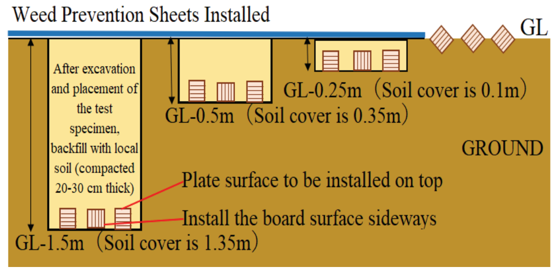


Figure3. Ground Environment Installations

Photo2. Ground installation conditions (Buried the test piece under the blue sheet)

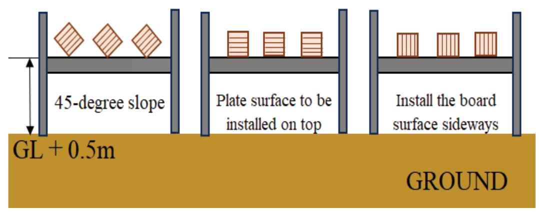


Figure4. Installation status in the air Installation status in the air

Photo3. Installation status in the air

The primary objective of this study is to utilize the durability data obtained from these exposure tests to facilitate the practical application of CLT technology in civil engineering. Table 6 illustrates the relationship between target civil engineering applications and their installation environments.

Table 6: Exposure Conditions and Corresponding Utilization Technologies

Relationship with the ground		Utilized technology			
		Construction laydown board	The slab of the station	Upright fence	Ground reinforcement
Above ground	GL+0.5m		●	●	
At ground level	GL±0m	●		●	
Underground	GL−0.25m	●			●
	GL−0.5m				●
	GL−1.5m				●

3 – RESULTS AND DISCUSSION

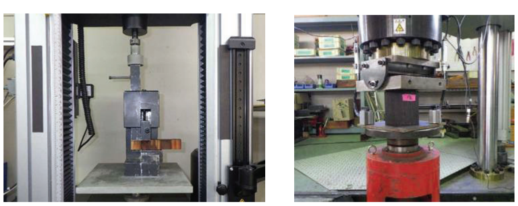
3.1 EXHUMATION OF 2-YEAR-OLD SPECIMENS

To assess the deterioration of CLT specimens exposed to various environmental conditions since 2021, a subset of the specimens was retrieved at two intervals: one year and two years after initial placement. The deterioration status was examined through visual observations and mechanical strength assessments, including longitudinal compression and block shear tests (Photos 4–9).

Photo 4. CLT test specimen after two years of exposure (subtropical zone)

Photo 5. Digging out the test piece (subtropical zone)

Photo 6&7. Observation of each specimen after removal



Photos 8& 9. block shear test （Left）
Longitudinal Compression Test （Right）

Digging out the test piece Specimens buried at a depth of GL-1.5 m were excavated using heavy machinery. Once retrieved, the surfaces of all specimens were lightly cleaned to remove dirt and debris as a pretreatment step for degradation assessment. The specimens were subsequently rinsed with water to eliminate residual soil, and comprehensive photographic documentation was conducted. Additionally, a high-resolution scanner (A4 size, minimum resolution of 600 dpi) was employed to capture detailed surface imagery. This procedure enabled the measurement of wet weight and color analysis across all six surfaces of each specimen to identify surface color variations over time.

Fig.5 and 6 illustrate the groundwater level fluctuations observed during the exposure period, serving as a reference for evaluating the degradation status of the specimens. Groundwater level measurements were not recorded for the temperate zone due to limitations in water level gauge functionality at significant depths, which resulted in the gauges measuring atmospheric pressure instead. Based on the recorded groundwater depth, Table 7 summarizes the relationship between the installation location and groundwater level for each specimen.

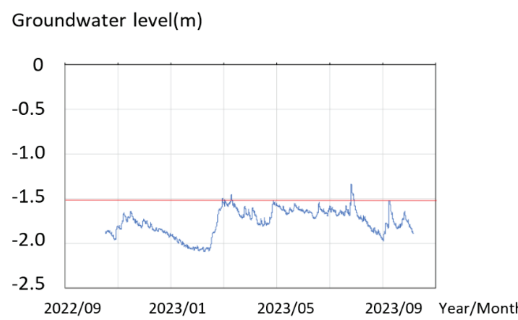


Figure 5 : Changes in groundwater level from one to two years after exposure(Subarctic zone)

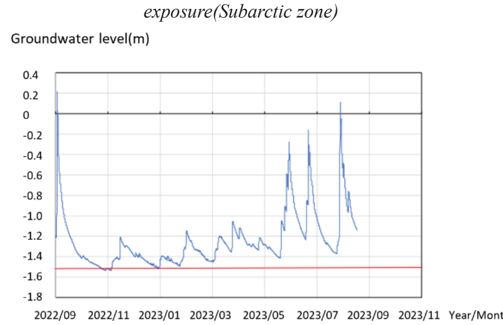


Figure 6. Changes in groundwater level from one to two years after exposure (Subtropical zone)

Table7: Relationship between installation location and groundwater level

Installation location	Relationship with groundwater level		
	Subarctic	Temperate	Subtropical
GL＋0.5m	Always above	Always above	Always above
GL±0m	Always above	Always above	Always above
GL-0.25m	Always above	Always above	Always above
GL－0.5m	Always above	Always above	Summer :Almost groundwater level Winter :Always above
GL－1.5m	Always above	Always above	Summer :below Winter :Groundwater level

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3.2 EVALUATION OF SOUNDNESS BY VISUAL OBSERVATION (EXPOSURE PERIOD: 2 YEARS)

Degradation Analysis

Fig.7–9 illustrate the percentage of specimens with visible signs of degradation for the different climatic zones and installation depths, with an above-ground reference group at GL+0.5 m. The specimens that were installed at depths equal to or below the groundwater level are indicated in red. Additionally, Table 8 gives degradation factors such as adhesive and lamina cracks, wood rot, and insect attack.

■RH ■API

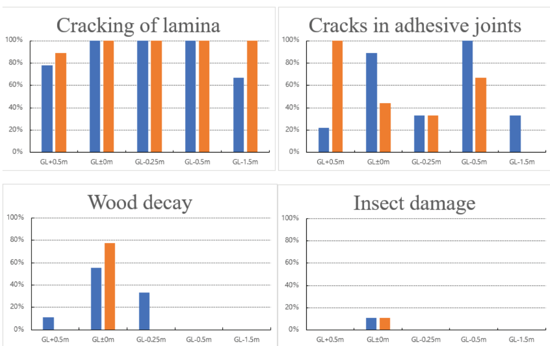

Figure 7. (Number of specimens in which each degradation item occurred)/(Total number of specimens) [%] Subarctic

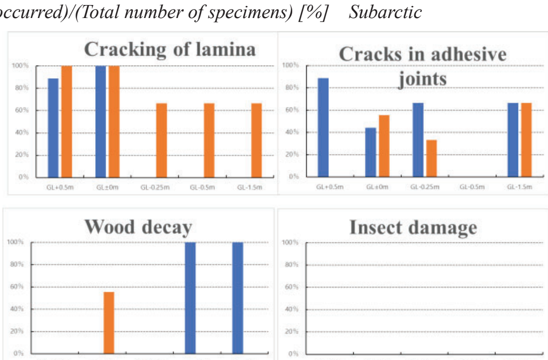

Figure 8. (Number of specimens in which each degradation item occurred)/(Total number of specimens) [%] Temperate

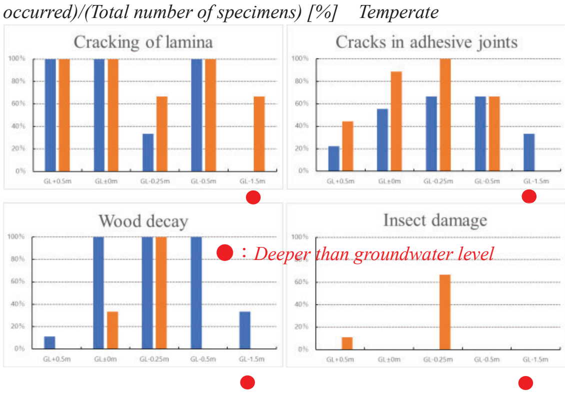

Figure 9. (Number of specimens in which each degradation item occurred)/(Total number of specimens) [%] Subtropical

Table 8: List of deterioration conditions

Deterioration status: ○: Slightly deteriorated; ◎: Deteriorated; ●: Severely deteriorated; ×: None

Installed location		Cracking of lamina	Cracks in adhesive joints	Wood decay	Insect damage
Subarctic	GL＋0.5m	○	◎	○	×
	GL±0m	○	○	○	○
	GL-0.25m	○	○	○	×
	GL-0.5m	○	○	×	×
	GL-1.5m	○	○	×	×
Temperate	GL＋0.5m	○	◎	×	×
	GL±0m	○	○	○	×
	GL-0.25m	○	○	×	×
	GL-0.5m	○	×	○	×
	GL-1.5m	○	○	○	×
Sub tropical	GL＋0.5m	○	●	○	○
	GL±0m	○	○	○	×
	GL-0.25m	○	○	○	○
	GL-0.5m	○	○	○	×
	GL-1.5m	○	○	○	×

Quantity of specimens observed

The number of specimens dug up and subjected to observation in this study is shown in Table 9.

Table 9: Number of specimens observed

Installation location	Subarctic		Temerate		Subtropical	
	RF	API	RF	API	RF	API
GL＋0.5m	9	9	9	9	9	9
GL±0m	9	9	9	9	9	9
GL-0.25m	3	3	3	3	3	3
GL－0.5m	3	3	3	3	3	3
GL－1.5m	3	3	3	3	3	3

Impact of Groundwater Level on the Durability of CLT

The wood piles that were installed below the groundwater level and existed underwater for a long period of time were confirmed to retain their function as wood piles [9]. Recent research, however, suggests that wood piles fully encased in clay soil remain decay-resistant even at shallow depths [10]. Additionally, studies on century-old wooden piles indicate that surface decay is influenced by groundwater fluctuations, while the core remains structurally sound [11].

In this study, CLT samples in the subarctic and temperate zones were set at depths that were consistently higher than the groundwater table. In the subtropical zone, the groundwater table varied seasonally, inundating the GL-

0.5 m samples in winter but exposing them in summer. At GL-1.5 m, the samples were generally above the groundwater table in winter but inundated in summer.

When the specimens were removed, all of the specimens at GL-1.5 m were wet only in the subtropical zone. We believe that this phenomenon proves that only the GL-1.5m specimens in the subtropical zone were at or below the groundwater table. This is supported by the fact that all specimens in the subarctic zone were dry. In the temperate zone, GL-1.5m was dry and GL-0.25m and GL-0.5m were wet. This is thought to be due to rain that fell just before the sampling.

As shown in Table 7, it was noted that GL-0.5m in the subtropical zone may have been affected by the groundwater table, but based on the results of this excavation, only GL-1.5m in the subtropical zone was affected by the groundwater table.

Biological Degradation (Decay and Insect Damage)

Biological degradation was negligible in the subarctic, but significant in the subtropics. This is probably due to temperature and humidity conditions suitable for fungal and insect activity. In particular, it was termites that were activated by suitable temperatures in the subtropics, confirming that termite damage was occurring. Photo 10 shows the conditions that support the presence of termites in the subtropical zone. In this study, CLT boards were buried in the ground in an upright position, separate from the specimens of the blocks in this study. When the buried board was excavated at the same time as the block specimen, termites were found to be living on the board only in the subtropical zone.

Photo 10. Termites found in the subtropics (on board)

Because groundwater level data were not readily available for the temperate zone, all test samples in the subarctic and temperate zone were presumed to be above the groundwater table. On the other hand, samples from the subtropical zone at GL-0.5 m and GL-1.5 m experienced seasonal submergence by groundwater and had lower decay rates compared to samples from the temperate zone at the same depth. This finding is consistent with the principle in wood pile studies that areas deeper than the groundwater table are less susceptible to decay and shallow areas are more susceptible [9].

Interestingly, two of the three RF-bonded samples at GL-0.25 m in the subtropical climate exhibited both insect attack and incipient wood decay (Photo 8). However, with the limited sample size, further studies are necessary to determine the relationship between adhesive type, installation depth, and susceptibility to insect attack.

Regarding decay, we note that for the specimens deeper than GL-0.5 m in the temperate zone, all six specimens only in RF had decay. However, all of them decayed only on the surface layer and did not reach the adhesive layer（Photo11）.

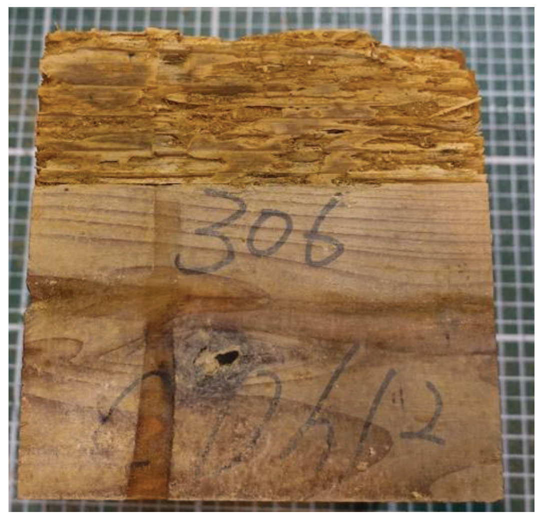

Photo 11. Surface decay（Temperate × APT × GL-0.5m）

The GL-0.25 m specimen in the temperate zone showed no decay at all in wet conditions. In the temperate GL-0.5m specimen, all of the API specimens decayed under wet conditions, but none of the RF specimens decayed at all. Since wood-rotting fungi are more likely to inhabit wet ground, it is necessary to determine the effects of adhesives and the relationship between wood-rotting fungi inhabitation and decay in future observations.

Physical Degradation (Adhesive and Lamina Cracks, Discoloration)

Compared with specimens retrieved after one year, lamina and adhesive joint cracking development was visible under all climatic exposures. With regard to the cracking of the laminae, the cracking of the specimens buried in the ground was generally smaller than that of the specimens in the air（Photos12, 13）.

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Cracking at the adhesive joints was a degradation mode specific to CLTs, resulting from the difference between shrinkage and expansion of the lamina, exacerbated by moisture-related cyclic stresses. The results of the current study were highly variable and did not confirm any trends due to the established variables (adhesive, installation site, and climatic conditions). Continued monitoring is needed to evaluate changes in climatic and location factors over time（Photo14）.

Photo12 &13. Cracking of laminae under the same conditions in subtropical × API Top : GL-0.1m Bottom : GL+0.5m

Photo14. Cracking at the adhesive layer Subarctic × API ×GL−0.5m

3.3 Mechanical Property Evaluation by Elemental Testing (Exposure Time: Two Years)

For the two strength tests, after visual observation, all specimens were soaked for three weeks to equalize the moisture content of all specimens and eliminate the influence of moisture content differences when comparing strength. To prevent cracking that occurred after removal from the soil from affecting the test results, the soaking time was increased and the moisture content was conditioned to be above the fiber saturation point (>60%). The specimens were then dried and weighed after testing.

Block Shear Test

Block shear tests were performed following the Japanese Agricultural Standards (JAS) method for cross-laminated timber. Four test pieces of 25 mm × 30 mm × 150 mm were cut from each cubic specimen, and 16 shear tests were performed for every specimen (Fig.10，Table10, photo15).

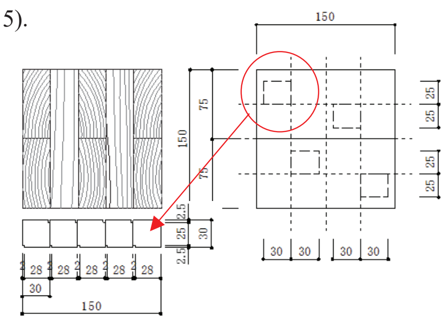

Figure 10. Drawing of specimens for block shear test

Table 10: Number of Block shear test

Installation location	Subarctic		Temerate		Subtropical	
	RF	API	RF	API	RF	API
GL＋0.5m	40	48	45	46	45	44
GL±0m	43	43	46	47	39	46
GL-0.25m	11	16	16	16	15	16
GL－0.5m	15	16	16	16	16	16
GL－1.5m	16	16	16	16	16	16

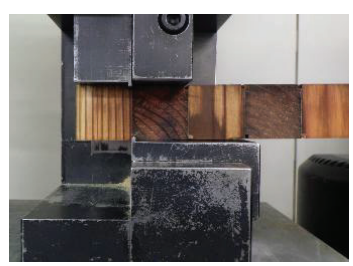

Photo15. Block Shear Test in Progress

Shear tests were performed on RF- and API-bonded specimens in three climate zones using a universal material testing machine (INSTRON 33R4466). However, extensive variability in shear strength under all conditions prevented comparative evaluations (Table 11). Due to the potential for loss in adhesion caused by

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environmental exposure, further long-term studies are needed to compare trends in adhesion performance.

Table 11: Results of block shear test

RF

Elapsed time	Maximum	Average※	Minimum
1 year	7.408	2.544	0.256
2 years	5.728	2.013	0.112

API

Elapsed time	Maximum	Average※	Minimum
1 year	5.056	2.495	0.080
2 years	5.024	2.000	0.352

※Mean values are calculated excluding 0 data

Previous study reported that the shear strength of glued laminated cedar (using API and phenol-resorcinol resin adhesives), which had not received the same preservative treatment as in the present study, declined as the wood decayed, but did not decline at all after 10 years of exposure if the wood had not decayed. However, if the wood is not decayed, the shear strength does not decrease even after 10 years of exposure [12]. It is necessary to verify the relationship between shear strength and wood decay of CLT in a ground environment, including whether the finding that adhesive performance is stable over a long period of time in the absence of wood decay can be applied to CLT in a ground environment.

Longitudinal Compression Test

The number of longitudinal compression tests performed is shown in Table 12. Longitudinal compression tests were conducted on the specimens in a saturated condition (Photo16).

Table12: Number of longitudinal compression tests

Installation location	Subarctic		Temerate		Subtropical	
	RF	API	RF	API	RF	API
GL＋0.5m	6	6	6	6	6	6
GL±0m	6	6	6	6	6	6
GL-0.25m	2	2	2	2	2	2
GL－0.5m	2	2	2	2	2	2
GL－1.5m	2	2	2	2	2	2

Photo16. A longitudinal compressive force was applied to the specimen in a saturated condition

Since the number of tests for each condition was small, the specimens in the ground environment except in air at GL + 0.5 m were grouped together, and the evolution of the test results from initial performance to the first and second year is shown in Fig.11. Comparing the outcomes of initial, one-year, and two-year tests, both longitudinal compressive strength and Young's modulus fell over time. Decayed samples exhibited significant losses in strength, particularly in the subtropical zone, where biological degradation was most severe. Subarctic samples, on the other hand, experienced moderate performance reductions. Future studies must address trends in biologically degradation-free samples to determine whether mechanical performance stabilizes or continues to deteriorate after two years.

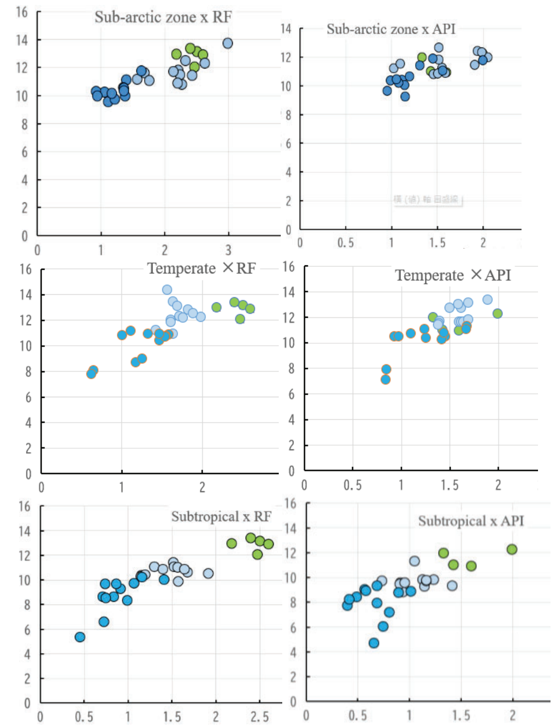

Figure11. Vertical Compressive Strength ●Initial ●1 year ●2 years

Vertical axis :Vertical compressive strength ［N/mm²］

Horizontal axis: Vertical compressive Young's modulus ［kN/mm²］

4 – CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSION

In this study, the durability performance of CLT under ground exposure conditions for a short-term condition of two years was evaluated by the deterioration conditions appearing on the material and mechanical strength. The results showed that the CLT suffered from cracking of the lamina and the adhesive layer regardless of the climatic conditions and the location of installation. However, with regard to lamina cracking, the cracks in the specimens in the subgrade environment were generally smaller than those in the specimens exposed to the air. As for biological degradation, none occurred in specimens below GL-0.5 m in the subarctic region. In the

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subtropical region, where termite infestation was observed in the buried soil, insect damage by termites was significantly observed in the specimens installed at GL-0.25 m, which is close to the ground surface. However, for the subtropical zone, decay was suppressed in specimens that were placed in a constantly wet condition below the groundwater table, which verified the findings [3] obtained so far with wood piles and other materials. Regarding decay, in specimens deeper than GL-0.5 m in the temperate zone, decay was observed in all specimens only in RF. However, in all specimens in this study, the decay was only in the surface layer and did not reach the adhesive layer. Mechanical testing showed a gradual decrease in longitudinal compressive strength over time, with the greatest decrease recorded in the biologically degraded samples. The shear strength of the blocks was highly variable, suggesting environmental effects on adhesive performance.

4.2 RECOMMENDATION

When CLT is actually used in the civil engineering field, it is expected to be used in many applications where medium- to long-term durability is required, although it may be used for only two years for temporary construction. Therefore, it is necessary to evaluate changes over time, focusing on cracks in the adhesive layer and lamina peculiar to CLT, through continuous monitoring. For subtropical areas where insect damage by termites has been observed, the relationship between the occurrence of insect damage and material strength should be confirmed. The data obtained from the long-term exposure tests will be compared with previously verified data on wood piles and CLT in the air to compile findings on the durability of CLT used under ground conditions. Based on the fact that no biological degradation damage was observed in CLT installed deep in subarctic conditions, we hope to optimize the use of CLT in geotechnical environments and establish a system for sustainable use of CLT in the civil engineering field without compromising their long-term structural reliability.

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