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MECHANICAL PROPERTIES OF GLUE LAMINATED TIMBER BY SMALL SIZE TREE SPECIES (CASE STUDY OF OKINAWAN FOREST)

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ABSTRACT: Local islanders have used Okinawan forest products for construction since ancient times. However, the present state is that the local forest trees have only a tiny diameter of 30 to 40 cm and 4 to 5 m in length on average. Because of that limited size, the timbers do not meet the size requirements for building construction, thus, they have been used only for low added value products. Therefore, to utilize those local timbers more valued products, the authors have proposed the glue laminated timber technique, which enables larger sections of structural elements to be used for building construction. This study selected four types of local timber to elaborate solid type and glue laminated timber type specimens to examine their applicability. The test consists of bending and fiber longitudinal compression tests to assess the mechanical properties of the Okinawan timbers. The results showed that the mechanical properties, such as strength and modulus of elasticity of solid and glue laminated timber, were equal to or stronger than solid timber. In addition, the mechanical properties of those timbers tested in this study were even stronger compared to extensively used timbers in Japan, such as Cedar and Japanese Cypress.

KEYWORDS: small size timber, glue laminated timber, bending strength, compression strength, modulus of elasticity

1 INTRODUCTION

With a sub-tropical climate, Okinawa Prefecture is home to many tree species not found elsewhere on Japanese islands. Several of these species have long been used for local large scale public buildings such as Shuri Castle and traditional private houses, shipbuilding, etc. However, the social and political shift to present modern Japan in the late 19th century caused the destruction of local forests. Due to this change, people started to consume timbers intensively, but the implant project of wood had not been executed properly. This poor forest preservation has continued over the years. Consequently, Okinawan sub-tropical woods recently have limited resources of trees, such as a tiny diameter of 30 to 40 cm and 4 to 5 m in length on average. Thus, it is known that the size of Okinawan solid wood is limited and too small for structural building materials, as shown in Figure 1[1].

Figure 1: Lumber in Okinawan Islands

Since the market of Okinawan timber is small as explained above, most local timbers are utilized for small products.
Among the total lumber processed, as shown in Figure 2, 35% is for chips for livestock bedding, 35% is for fuel wood, and the remaining 30% is used for lumber elements. Among the last item, the main products processed are furniture, accessories, and other elements with small demand for timber volume.

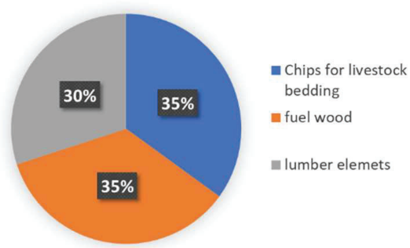

Figure 2: Use of the Okinawan lumber

The characteristic of the lumber produced in Okinawan islands such as Ryukyumatsu (Pinus luchuensis), Itajii (Castanopsis sieboldii), Iju (Schima wallichii) and Inumaki (Podocarpus macrophyllus) is that they have in average a density of 0.6 gr/cm^3[1]. This density is higher than the Cedar (0.34 gr/cm^3) and Japanese Cypress (0.42 gr/cm^3), which are more prevalent lumber in the Japanese timber industry. However, since Okinawan timber's mechanical properties are not standardized as the other

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species, they can not be used as structural elements for building construction due to the lack of technical information.
In this study, we would like to consider using this timber as a higher value-added structural material for construction. Therefore, we have proposed using small-sized Okinawan lumber for glue laminated timber (GLT), enabling high-quality structural elements with large sections with fewer defects.
The research focuses on whether the mechanical properties of the Okinawan timber can be improved by using GLT and comparing them with the Cedar and Japanese Cypress values. Also, this paper proposes a reference strength value to be used in the structural design.
In this paper, full-scale specimens of solid wood and glued laminated timber from Okinawa Prefecture were prepared and tested in bending and compression to assess their mechanical properties.

2 METHOD

2.1 MATERIAL AND SPECIMENS

Four tree species were selected for this study, Ryukyumatsu (Pinus luchuensis), Itajii (Castanopsis sieboldii), Iju (Schima wallichii), and Inumaki (Podocarpus macrophyllus). The timber was obtained from the Kunigami-village, Okinawa Prefecture's forestry cooperative, and was used to make solid and glue laminated timber specimens.
The specimens were manufactured following the Japan Housing and Wood Technology Center (HOWTEC) regulations[2]. Figure 3 shows the dimension of the specimens. Three solid and six GLT specimens were tested from each tree species, as shown in Table 1.

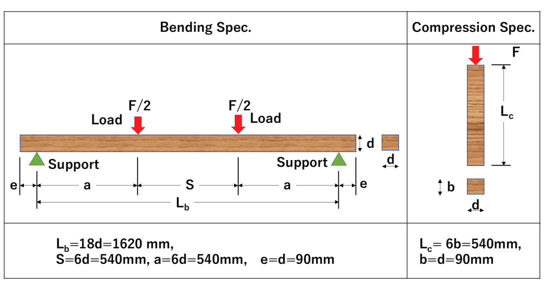
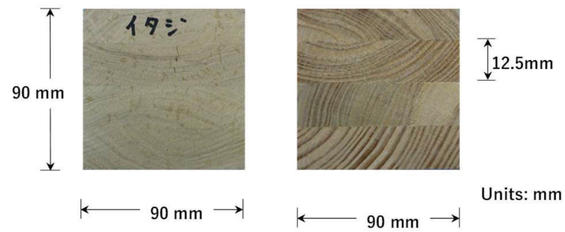


Figure 3: *Details of specimens*

Table 1: Specimens List

Test	Timber Type	Solid		GLT	
		Size (mm)	No. of Spec.	Size (mm)	No. of Spec.
Bending Spec.	Ryukyumatsu	90x90x1800	3	90x90x1800	6
	Itajii	90x90x1800	3	90x90x1800	6
	Iju	90x90x1800	3	90x90x1800	6
	Inumaki	90x90x1800	1	80x80x1600	1
Comp. Spec.	Ryukyumatsu	90x90x540	3	90x90x540	6
	Itajii	90x90x540	3	90x90x540	6
	Iju	90x90x540	3	90x90x540	6
	Inumaki	90x90x540	1	80x80x480	1

The glued laminated wood specimens were made of four layers of lamina boards, which were finger-jointed and glued together with water based polymer isocyanate adhesive, as shown in Figure 4. Also, Figure 5 shows the details of the finger joints.



(a) Solid *(b) GLT*

Figure 4: *Section of specimens*

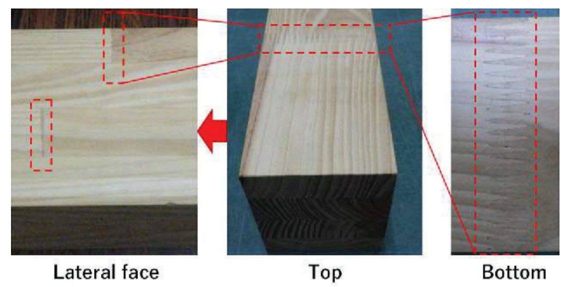


Figure 5: *Detail of the finger joint*

2.2 EXPERIMENTAL METHODOLOGY

In this test, bending and longitudinal compression tests were conducted on solid and glued laminated timbers following the Manual for Strength Testing of Structural Timbers[1)]. The testing machine was a universal testing machine (Shimadzu Corporation, UH-FC, maximum capacity 2000 kN) at the experimental testing laboratory of the Faculty of Engineering, University of the Ryukyus. The loading rate was constant displacement so that the time to reach maximum load was at least one minute. The density and moisture content of all specimens were determined before testing. For moisture contents calculations, pieces cut from each specimen were placed in an oven from 101°C to 105°C until the quasi constant weight was obtained.

1) Bending Test
The loading system for the bending test is shown in Figure 6. This test determines the bending strength MOR_b and the bending modulus of elasticity MOE_b. The bending test was performed using the four points load method to have pure bending between the applied loads.
The load cell attached to the testing machine and the displacement transducer installed on the specimen were used to record the bending loads and deflections at the center of the span. A jig was attached to the neutral axis at the center of the specimen to measure the deflection.

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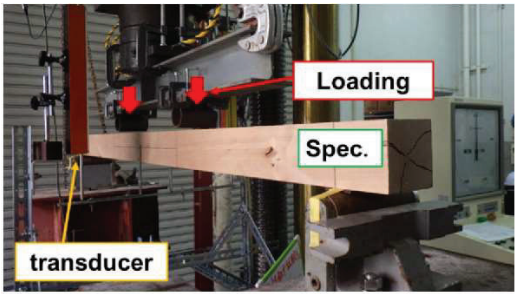

Figure 6: *Bending Test*

The displacements on both sides were measured with a displacement transducer (SDP-3000), and the average value was taken. Using the values measured in the test, MOR_b and MOE_b were calculated from the following equations (1) and (2) [2].

$$MOR_b = \frac{aP_m}{2Z} \quad (1)$$

$$MOE_b = \frac{a(3L^3 - 4a^2)(F_2 - F_1)}{48(w_2 - w_1)} \quad (2)$$

Where MOR_b=bending strength (N/mm^2), MOE_b= modulus of elasticity (N/mm^2), a = distance between the two supports (mm), P_m=maximum load, a=distance between loading points and support, Z= section modulus (mm^3), ΔP= increment of load at the elastic range (N), I=moment of inertia (mm^4), F_1-F_2= Incremental load on the straight line portion of the load-deformation curve F_1=Pm /10 、 F_2=4P_m/10 [N], w_2-w_1= Incremental deformation corresponding to F_2-F_1 (mm).

2) Compression test

The loading system for the longitudinal compression test is shown in Figure 7. This test determines the longitudinal compressive strength MOR_c and the longitudinal compressive modulus of elasticity MOE_c.

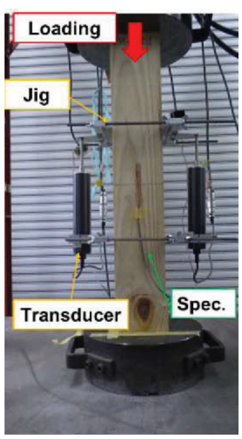

Figure 7: *Comp. Test*

The specimens were loaded using a universal testing machine with a spherically seated load head, allowing the application of uniform compressive load without creating bending stresses. The compression strains were measured by placing a jig located at the center of the specimen (l = 200 [mm]) with a displacement transducer (CDP-50). This jig was located 170 mm from both ends of the specimens. Using the values measured in the test, MOR_c and MOE_c were calculated from the following equations (3) and (4).

$$MOR_c = \frac{P_c}{A} \quad (3)$$

$$MOE_c = \frac{l(F_2 - F_1)}{A(w_2 - w_1)} \quad (4)$$

Where MOR_c=compression strength (N/mm^2), MOE_c= modulus of elasticity (N/mm^2), A = section of the specimen (mm), P_c=maximum load, l = test length (200mm), F1-F2= Incremental load on the straight line portion of the load-deformation curve F_1=Pm /10, F_2=4P_m/10 [N], w_2-w_1=Incremental deformation corresponding to F_2-F_1 (mm).

3 RESULTS

3.1 BENDING TEST

The strength-deflection curves for bending specimens are shown in Figure 8. The maximum strength value of the GLT specimens tended to be higher than that of the solid timber. In this study, the solid specimens showed a bigger deflection capacity before the failure than GLT ones. For example, solid specimens RM-S-B2 and RM-S-B3 showed deflection values greater than 50 mm, while GLT specimens showed deflection values around 35 mm.

The GLT specimens of Ryukyumatsu showed quite a similar trend in bending tests.

Specimens of Itaji and Iju showed similar bending behavior. The solid ones presented more significant deflections before failure than the GLT specimens.

In the case of Inumaki, there were no differences between solid and GLT specimens because of the limited number of samples.

Table 2 summarizes the bending test results. As the table shows, the bending strength values of GLT specimens were about 1.0 to 1.4 times higher than solid ones. The bending modulus of elasticity of GLT specimens was approximately 1.1 to 1.5 times higher than solid ones.

The measured water contents varied from 10 to 25 % depending on the period that passed since the tree was cut off. The difference between the solid and GLT specimens within the same kind of timber ranged ±5%, and then it was assumed to be no influence on the bending strength results.

Concerning the failure patterns, three types were observed. In some specimens, the failure occurs at the bottom face of specimens, as shown in Figure 9 (a), where the higher bending stresses occur.

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In other cases, the failure starts from knots located at the lateral face, as shown in Figure 9 (b). In this particular case, several lateral face knots influenced the failure.
On the other hand, the failure of GLT specimens tended to occur from the finger joints, as shown in Figure 9 (c), especially those located at the bottom face between load points where the maximum bending stresses occur.

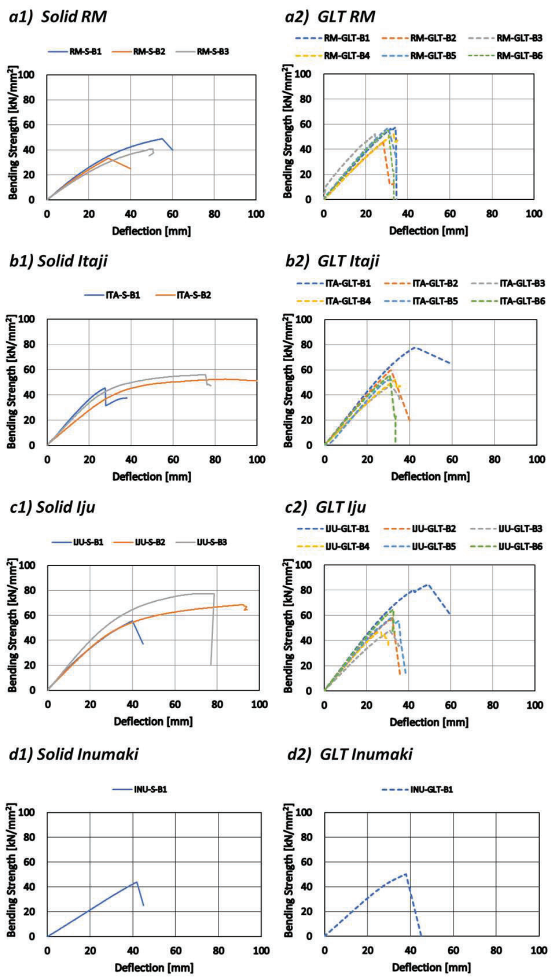
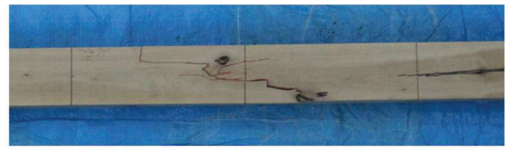


Figure 8: *Bending strength vs. deflection*

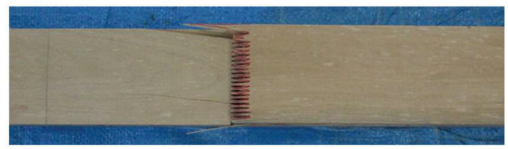
Table 2: *Bending Test Results*

Timber	Type	No of Spec.	Density (kg/m³)	WC (%)	Max Load (kN)	Bending Strength (N/ mm²)	Bending Elastic Modulus (kN/ mm²)
Ryukyumatsu	Solid	3	571.1 (24.9)	16.6 (1.3)	18.4 (2.9)	41.0 (6.4)	7.8 (0.6)
	GLT	6	681.5 (9.9)	20.8 (0.6)	24.2 (1.7)	53.8 (3.8)	11.6 (0.7)
Itajii	Solid	3	818.7 (57.7)	24.1 (2.3)	23.1 (2.0)	51.3 (4.3)	10.4 (1.3)
	GLT	6	732.3 (11.3)	18.2 (1.1)	26.4 (4.4)	58.7 (9.9)	12.1 (1.3)
Iju	Solid	3	643.1 (23.4)	10.7 (0.3)	30.2 (4.4)	67.1 (8.9)	11.3 (1.0)
	GLT	4	639.8 (10.8)	16.5 (1.1)	31.1 (5.2)	69.1 (9.7)	13.1 (0.6)
Inumaki	Solid	1	485.9 (-)	21.2 (-)	15.7 (-)	34.9 (-)	5.3 (-)
	GLT	1	559.0 (-)	25.2 (-)	17.7 (-)	49.8 (-)	7.6 (-)

(a) Failure from sound part (case of solid specimen)



(b) Failure from the knot (case of solid specimens)



(c) Failure from the finger joints knot (case of GLT specimens)

Figure 9: *Failure Pattern*

Even though the failure of the GLT specimens occurred at the bottom due to the finger joints, all these specimens showed higher bending strength than their solid specimens counterparts. Therefore it is possible to infer that the finger joints do not influence the maximum strength values.

3.2 COMPRESSION TEST

The results of the longitudinal compression test are shown in Figure 10. The maximum compression strength value of GLT specimens was higher than that of the solid timber except for Inumaki specimens.
The solid and GLT specimens of Ryukyumatsu showed strength strain curves behavior proportionally. In both cases, some specimens showed bigger deformation capacity while others failed shortly after reaching the maximum strength. Also, the GLT specimens of Ryukyumatsu showed similar behavior in the initial stage at the elastic range.
It seems reasonable to suppose that a bigger strain means a larger deformation capacity without collapse. The solid specimens of Itaji showed more deformation capacity than the specimens of Iju. However, this group presented bigger compressive strengths.
The GLT specimens of Itaji and Iju have similar strength and deformation capacity trends. In this sense, solid and GLT specimens of Inumaki showed quite similar behaviors.
Table 3 summarizes the compression test results. As the table shows, the compression strength values of GLT specimens were about 2.2 times higher than solid ones.
The compression bending modulus of elasticity of GLT specimens was approximately 1.6 times higher than solid ones.
The specimen water contents were measured just after the experiment and varied from 10 to 22 % depending on the period since the tree was cut off. The difference between the solid and GLT specimens within the same kind of

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timber ranged ±5%, and then it was assumed to be no influence on the bending strength results.

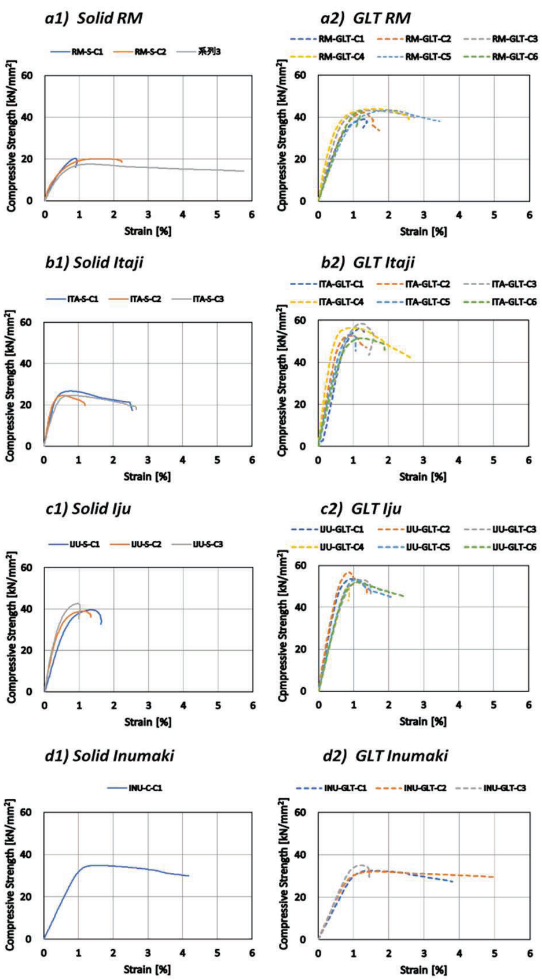


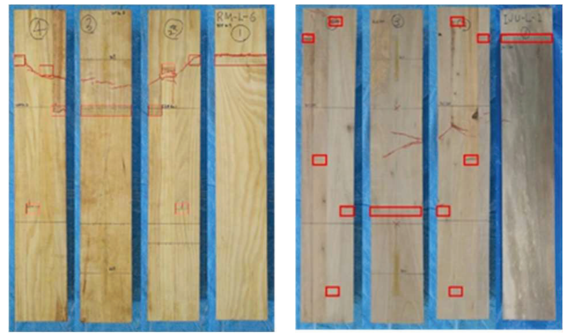
Figure 10: *Compression strength vs strain*

Table 3: *Compression Test Results*

Timber	Type	No of Spec.	Density (kg/m³)	WC (%)	Max Load (kN)	Comp. Strength (N/ mm²)	Comp. Elastic Modulus (kN/ mm²)
Ryukyumatsu	Solid	3	548.7 (13.1)	14.8 (0.4)	155.3 (10.9)	19.2 (1.3)	7.3 (0.9)
	GLT	6	665.7 (20.8)	14.0 (2.2)	343.3 (12.9)	42.4 (1.6)	11.6 (2.7)
Itajii	Solid	3	870.3 (20.5)	14.1 (2.3)	198.0 (16.0)	24.4 (2.0)	14.0 (0.8)
	GLT	6	731.6 (16.5)	22.4 (4.3)	442.9 (20.3)	54.7 (2.5)	18.1 (4.4)
Iju	Solid	3	711.8 (7.5)	10.7 (0.3)	327.0 (12.9)	40.4 (1.6)	16.0 (3.1)
	GLT	6	653.1 (12.4)	19.5 (0.4)	430.5 (16.9)	53.1 (2.1)	16.0 (2.8)
Inumaki	Solid	1	541.8 (-)	21.2 (-)	282.6 (-)	34.9 (-)	7.0 (-)
	GLT	3	571.8 (3.1)	19.5 (0.4)	212.8 (8.3)	33.3 (1.3)	7.2 (0.5)

Each value indicates the mean value, the numbers in parentheses indicate the standard deviation, and the symbol (-) are not calculable.

Concerning the failure patterns of GLT, two types were observed. In some specimens, the failure occurs at the finger joint, as shown in Figure 11 (a). In another case, the failure occurs in the specimens' middle part with no influence of finger joints, as shown in Figure 11 (b).



(a) Failure on finger joint (b) Failure on the middle part

Figure 11: *Failure pattern of compression specimens*

4 STANDARD MATERIAL STRENGTH

Cedar and Japanese Cypress are extensively used for building construction in Japan. Those timbers have authorized standards, so the authors compared the mechanical properties of Okinawan timbers with them. The test results proved clearly that Okinawan timbers are strong enough to be applied to structural building elements.

The reference strength F can be obtained from Equations (5) and (6). The coefficient K for obtaining the 5% lower limit at the 75% confidence level is the value shown in Tables 4 and 5, depending on the number of specimens. Based on this, the reference strength in bending of glued laminated wood in this study was calculated and compared with the reference strength of ungraded timber described by the Architectural Institute of Japan[5].

$$ {}_0F = \bar{x} - K \times s.d. \qquad (5) $$

$$ F = Kt \times {}_0F \qquad (6) $$

Where:

${}_0F$: is the Reference Strength Characteristic Value

$\bar{x}$: average value (average experimental value)

K: Value based on the number of specimens (coefficient for obtaining the lower 5% limit at the 75% confidence level)

$s.d.$: Standard deviation

Kt: Deterioration Effect Factor (In this case, it is considered the timber has no deterioration, therefore Kt is taken a 1)

Table 4: *Bending standard material strength*

Timber	Type	Bending Strength (N/ mm²) MOR	S.D.	Bending Standard Strength F_b
Ryukyumatsu	Solid	41.0	6.4	20.9
	GLT	53.8	3.8	44.9
Itajii	Solid	51.3	4.3	37.6
	GLT	58.7	9.9	35.6
Iju	Solid	67.1	8.9	39.0
	GLT	63.6	11.7	36.3
Inumaki	Solid	34.9	-	34.9
	GLT	49.8	-	49.8

Table 5: Compression standard material strength

Timber	Type	Comp. Strength MOR (N/ mm²)	S.D.	Comp. Standard Strength F_c (N/ mm²)
Ryukyumatsu	Solid	19.2	1.3	14.9
	GLT	42.4	1.6	38.7
Itajii	Solid	24.4	2.0	18.2
	GLT	54.7	2.5	49.8
Iju	Solid	40.4	1.6	35.3
	GLT	53.1	2.1	48.3
Inumaki	Solid	33.3	1.3	29.2
	GLT	19.2	1.3	14.9

Table 6: Compression standard material strength[5]

Tree Species			Standard Strength (N/mm²)	
			Bending	Comp.
Conifer	Category I	Pine	28.2	22.2
	Category II	Larch, Cypress	26.7	20.7
	Category III	Hemlock	25.2	19.2
	Category IV	Fir, Cedar	22.2	17.7
Hardwood	Category I	oak	38.4	27.0
	Category II	Chestnut, Zelkova	29.4	21.0

Although a small number of timber specimens for all four Okinawan timbers ranged from three to six specimens each except Inumaki, the result of the GLT bending test showed 1.4 times stronger than the standard bending strength of Cedar on average. Compared with another standard value of Japanese Cypress, the GLT performed even 1.7 times higher on average. On the other hand, concerning a longitudinal compression test, the GLT showed twice as strong as Cedar and Japanese Cypress. All those results encourage using the Okinawan GLT for building structural elements, as shown in Table 6. However, the number of specimens was limited, as mentioned above. More importantly, the data was dispersed for Itajii and Ijyu, which authors cannot find a particular reason to explain within this study.

In addition, in comparing solid timbers and the GLT, the GLT appeared to be higher figures in the bending and longitudinal compression tests, with a few exceptions.

5 DISCUSSIONS AND CONCLUSIONS

The results showed that the GLT of four kinds of Okinawan timbers, Ryukyumatsu, Itajii, Ijyu, and Inumaki, were stronger regarding the mechanical properties for both bending and compression tests compared to the same kinds of solid timbers. The material difference between GLT and solid timbers is noticeable because, naturally, the solid ones have knots and defects on the surface of timbers, whereas GLT does not. Therefore, it seems reasonable to suppose that this higher strength is due to the absence of knots and defects in timbers(GLT) when they are glue-laminated.

Here is one concern about the use of GLT for building construction. Using glue, some people are concerned about the strength of the adhesive and the part of the joints. However, our test results proved enough strength of timbers in bending and compression with finger joints. There is considerable validity to the test results, though it should not be pushed too far. For instance, further research should be included the deterioration of glue in the long term and /or to consider some different types of finger joints.

Historically Okinawan timbers had been limited and highly valued for building construction; however, recently, they have not been used for other reasons. One reason is that there is no technical endorsement of mechanical properties, and another is the small size in length and diameter. Thus, the Okinawan timber industry has shrunk over the years. If the GLT method is introduced as effective timber utilization, the Okinawan timbers can be used for structural building elements in this situation. Consequently, local industry and the economy can be boosted simultaneously.

From the viewpoint of industry activation, it should be considered in several aspects carefully. One is the production systems, and another is the market, in other words, the balance of demand and supply in the local economy and society. Additionally, since the growth rate of overall Okinawan timbers is low, the availability tends to be naturally limited.

In terms of GLT production in Okinawa, as explained before, the material supply itself is limited, so lucrative market sales cannot be expected in straight forward. For this reason, these Okinawan timbers, Ryukyumatsu, Itajii, Iju, and Inumaki, should be treated as least valued timbers so that the GLT processing system should not be prepared for a massive production system. Instead, after using solid Okinawan timbers for public historical and traditional wooden buildings, denominated as important cultural properties, the rest of the timber should be processed for the GLT production system for better-respected utilization. There is a general agreement that GLT production would work supportively instead of mainly in the timber industry. GLT production works even in a small but feasible industry in the local economy and society.

From the contrary viewpoint of industrialization, the authors considered the GLT production system might expand the effective timber use. Eventually, the system helps the sustainable circle of forest conservation, plantation, and utilization. It is expected that the loss of small timbers will be reduced remarkably because those timbers used to be assumed as residuals would convert into even stronger timber products by the GLT technique. At the same time, the consumption of timbers and the surplus of timbers would be managed under more controlled conditions because timber stock can be integrated as GLT products.

In conclusion, GLT of Okinawan timbers can be reliable for building structural elements.

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