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Static Bending Strength Performances of Wood-Aluminum Hybrid Laminated Material

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Wood has a low density and high strength performances parallel to the grain. We made three-ply hybrid laminated material reinforced by laminating aluminum alloy laminae on sugi (Japanese cedar) wood beam, and investigated the influence of the thickness of aluminum lamina, the arrangement of lamina and the deflection caused by shear force on its static bending strength performances. Epoxy resin was used as adhesive.

The modulus of elasticity (MOE) and modulus of rupture (MOR) of sugi wood-aluminum hybrid laminated material increased markedly with increasing thickness of aluminum lamina, and the extent of increase was greater in horizontally laminated type (H type) than in vertically laminated type (V type). The measured values of MOE for H type and V type were much lower than the values calculated from the true MOE of individual lamina. The difference between the measured and the calculated values was smaller in V type than in H type. This can be explained in terms of the effect of the deflection caused by shear force on the MOE.

It was found that a material with a relatively low density and very high bending strength performances can be manufactured by laminating aluminum alloy laminae on sugi wood beam.

Key Words: hybrid laminated material, sugi wood, aluminum alloy, modulus of elasticity, modulus of rupture.

1. INTRODUCTION

Wood has a low density and high strength performances parallel to the grain, and is used as a structural material. Furthermore, it is possible to improve the strength performances parallel to the grain by the reinforcement with a material having higher strength performances than those of wood.

Recently, Attempts have been to manufacture efficient hybrid laminated materials that metal plate and carbon fiber sheet are laminated on wood beam respectively, and their strength performances have been examined [1, 2]. There are also a few researches in hybrid laminated materials reinforced with aluminum sheet on wood beam. The analysis on mechanical behavior of the aluminum sheet for a rectangular composite beam and a trapezoid composite beam was conducted by Mark [3, 4]. The comparison between the calculated and the observed values for horizontal and vertical wood laminated beams which were assembled with aluminum sheet inserted between selected layers was also conducted by Sliker [5].

In this study, to clarify the static bending strength performances of two types of materials laminated with aluminum alloy on sugi (Japanese cedar) wood beam horizontally and vertically, we investigated the influence of the thickness of aluminum laminae, the arrangement of lamina and the deflection caused by shear force on its static bending strength performances.

2. MATERIALS AND METHODS

2.1 Specimen

Sugi(Japanese cedar, *Cryptomeria japonica* D. Don) with densities in the range of 0.374~0.409 Mg/m^3 and aluminum alloys 1mm, 2mm and 3mm thick with densities in the range of 2.71~2.74 Mg/m^3 were used as materials. The alloy number for 1mm thick was A5052P and those for 2mm and 3mm thick were A6063BE in Japanese industrial standard. Aluminum laminae with dimensions of 1, 2, 3mm × 20mm × 340mm and sugi wood beams with those of 14, 16, 18mm(T) × 20mm(R) × 340mm(L) and 20mm(T) × 14, 16, 18mm(R) × 340mm(L) were prepared from the materials. The aluminum laminae were laminated

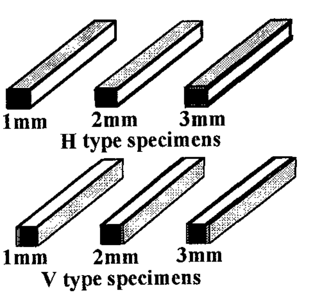

Fig.1. Wood-aluminum laminated composite beams (20 × 20 × 340mm).
Note : H : Horizontally laminated beam specimens, V : Vertically laminated beam specimens, 1, 2, 3mm : Thickness of aluminum lamina.

on sugi wood beam horizontally (H type) and vertically (V type), and sugi wood-aluminum composite laminated beams with 20mm×20mm×340mm were manufactured as shown in Fig.1. A two-part type epoxy resin adhesive was used and the amount of spread was 350g/m^2. The number of each type of specimen was 4.

2.2 Static bending test

Static bending test for hybrid laminated wood specimens was conducted by four-point loading. The span was 300mm, and the deflection was measured with a dial gauge. From true MOE of individual laminae, the calculated value for each specimen was obtained using the equivalent cross section method (Eq.1), and compared with the observed values of hybrid laminated beam specimen.

$$EI = E_1I_1 + E_2I_2 + E_3I_3 \qquad (1)$$

where E is the modulus of elasticity, E_1, E_2, E_3 are the modulus of elasticity of individual laminae. I is the moment of inertia for the whole cross section, and I_1, I_2, I_3 are the moment of inertia for individual laminae about the neutral axis of cross section.

3. RESULTS AND DISCUSSION

3.1 Stress-strain curve

Typical examples of stress-strain curves for aluminum alloys, sugi wood and wood-aluminum laminated composite beams are shown in Figs.2 and 3.

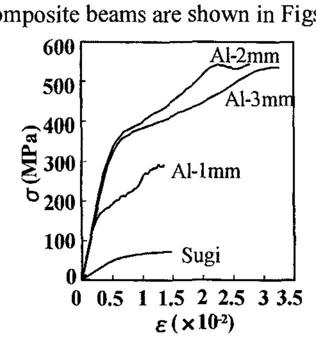

Fig. 2. Stress-strain curves for aluminum alloys and sugi wood.
Note : 1mm, 2mm, 3mm : Thickness of aluminum lamina.

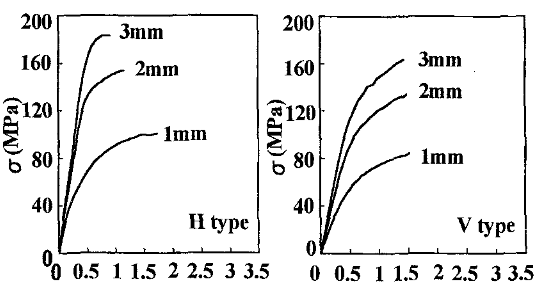

Fig. 3. Stress-strain curves for wood-aluminum laminated composite beams.
Note : 1mm, 2mm, 3mm : Thickness of aluminum lamina.

For aluminum laminae 2mm and 3mm thick, long curve regions were observed beyond the proportional limit. Their breaking strains were two times greater than that of sugi wood. The breaking strain of H type decreased with increasing thickness of aluminum lamina, whereas the breaking strains of V type were nearly equal to that of sugi wood beam and did not depend on the thickness of aluminum lamina.

3.2 Bending modulus of elasticity

3.2.1 Effect of aluminum lamina thickness

The moduli of elasticity (MOEs) of aluminum alloys showed 78.6GPa for 1mm thick, 76.8GPa for 2mm thick and 70.9GPa for 3mm thick. They were 7.1~7.9 times greater than 9.93GPa of sugi wood.

The relations between the modulus of elasticity and the aluminum lamina thickness for wood-aluminum laminated composite beams are shown in Fig.4. The MOEs of H type and V type increased proportionally and markedly with increasing aluminum lamina thickness. Those of H type were 1.9 times for 1mm thick, 3.0 times for 2mm thick and 3.6 times for 3mm thick that of sugi wood. The extent of increase was 1.8~2.4 times higher in H type than in V type. This can be explained in terms of the fact that the moment of inertia of cross section of aluminum with a high MOE is greater in H type whose aluminum laminae is arranged in surface layers farther from the neutral axis.

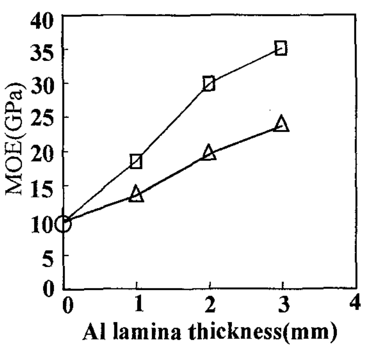

Fig. 4. Relation between MOE and aluminum lamina thickness for wood-aluminum laminated composite beams.
Legend : □: H type, △ : V type, ○ : Sugi wood.

3.2.2 Effect of deflection caused by shear force

Deflection of beam for four point bending is shown as follow:

$$y_a = y_m + y_s = \frac{Pl_1(3l^2 - 4l_1^2)}{4bh^3E} + \frac{kPl_1}{2bhG} = \frac{Pl_1(3l^2 - 4l_1^2)}{4bh^3E}\left[1 + \frac{2.4h^2}{3l^2 - 4l_1^2}\cdot\frac{E}{G}\right] \qquad (2)$$

where y_m is the deflection caused by bending moment, y_S is the deflection caused by shear force, E is the true MOE, G is the shear modulus, P is the applied load, b, h are the width and height of beam, l is the span, l_1 is the distance between loading point and supporter, and k is 6/5 in the case of rectangular cross section[6].

From Eq.(3), MOE calculated from the deflection caused by bending moment is given as follows:

$$E = E_a(1+\phi) \qquad (3)$$

where E_a is the apparent MOE, and $\phi = 2.4h^2/(3l^2-4l_1^2)\cdot(E/G)$.

The true MOEs of the hybrid laminated materials were obtained using Eq.(3) from the true MOEs of sugi wood beam and aluminum laminae.

The shear modulus(G) of aluminum lamina was obtained using the following Eq.(4)

$$G = E/2(1+\nu) \quad (4)$$

where E is the measured MOE, and ν is the Poisson's ratio(0.34) [7].

The true MOEs of aluminum laminae were obtained using E/G calculated from the measured MOE and the shear modulus of aluminum lamina obtained using Eq.4 and Eq.5. On the other hand, the true MOE of sugi wood was obtained using E/G calculated from the relation between the square of ratio of thickness to span and the compliance ($1/E_a$) as described in a previous report [8]. Furthermore, the percentages of deflection caused by shear force versus total deflection by bending moment and shear force were obtained as the following equation:

$$Y_s = 100(y_a - y_m)/y_a = 100(E - E_\alpha)/E (\%) \quad (5)$$

where E_α is the measured MOE, and E is the ture MOE.

The percentage of deflection caused by shear force(Y_s) of aluminum lamina showed very low values(0.003～0.022%), and increased with an increase in aluminum lamina thickness. Those values were markedly lower than that of sugi wood (7.69%). This was because the E/G of sugi wood was about 7.4 times as high as those of aluminum lamina and the l/h of the latter was 6.7~20 times as great as those of the former.

The ratios of the measured values to the calculated ones for H type and V type are shown in Fig.5.

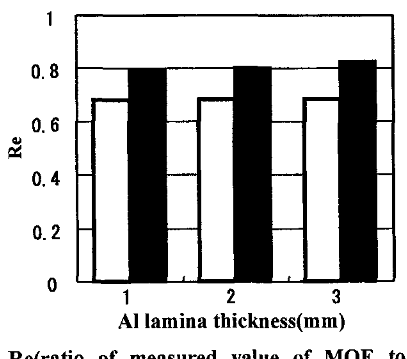

Fig. 5. Re(ratio of measured value of MOE to value calculated from true MOE of laminae) for wood-aluminum laminated composite beams.
Legend : □ : H type, ■ : V type.

For H type laminated horizontally, the ratios showed 0.68 for every thickness of aluminum lamina, and the measured values were found to be much lower than the calculated ones. However, the ratios(0.79～0.82) were greater in V type laminated vertically than in H type. This can be explained in terms of the effect of deflection caused by shear force on the MOE, depending on E/G in Eq.(2). In the previous reports [8, 9], we took into consideration the contribution of glue line to the MOE of laminated wood in order to examine the effect of deflection caused by shear force on the MOE of laminated wood. But in this study, the contribution of glue line was ignored because the MOEs of hybrid laminated materials were very high while the MOE of epoxy resin used was low. Therefore, the true MOE of hybrid laminated material calculated using Eq.(1) from the true MOE of laminae was used. The percentage of deflection caused by shear force versus total deflection(Y_s) was calculated using the following equation:

$$Y_s = 100(y_a - y_m)/y_a = 100(E_\beta - E_\alpha)/E_\beta (\%) \quad (6)$$

where E_α is the measured MOE, and E_β is the true MOE of hybrid laminated material calculated from the true MOE of laminae.

Table 1 shows the Y_s values. The Y_s of H type showed high values of 31.8～32.4%, whereas the Y_s of V type was lower than that of H type. This is considered to be mainly because the E/G of H type had higher values than that of V type. For H type, E was increased much more than G by laminating aluminum laminae on sugi wood beam horizontally. On the other hand, the extent of increase in E for V type laminated vertically was much smaller than that for H type, but the extent of increase in G for V type was much greater than that for H type.

The Y_s of both types decreased only slightly with increasing aluminum lamina thickness.

Table 1. Effect of deflection caused by shear force on MOE for wood-aluminum laminated composite beams.

Type	T(mm)	E_α(GPa)	E_β(GPa)	Y_s(%)
H	1	18.4	27.2	32.4
	2	29.8	44.0	32.2
	3	35.1	51.6	31.8
V	1	13.5	17.1	20.7
	2	19.4	24.3	20.2
	3	23.6	28.7	17.8

Note : T : Thickness of aluminum lamina, $Y_S = 100 (E_\beta - E_\alpha)/E_\beta$, H : H type, V : V type, E_α,: Measured MOE, E_β : True MOE calculated from true MOE of laminae.

3.3 Bending modulus of rupture

The moduli of rupture (MORs) of aluminum alloys showed 294MPa for 1mm thick, 541MPa for 2mm thick and 536MPa for 3mm thick. They were 4.1～7.5 times greater than 72.5MPa of sugi wood. The MOR of 1mm thick was much smaller than those of 2mm and 3mm thick.

The relations between the MOR and the aluminum lamina thickness for wood-aluminum laminated composite beams are shown in Fig.6. The MORs of H type and V type increased with increasing aluminum lamina thickness. They increased markedly and linearly for 2mm and 3mm thick, but the extent of increase for 1mm thick was smaller because aluminum lamina 1mm thick had low value of MOR. The MORs of H type showed 1.3 times for 1mm thick, 2.1 times for 2mm thick and 2.6 times for 3mm thick that of sugi wood. The MORs of V type were somewhat lower than those of H type.

It was found that for H type, the extent of increase of MOR was smaller than that in MOE. This reason is considered to be partly because the breaking strain of H type decreased remarkably with increasing aluminum lamina thickness and that of V type including 2mm or 3mm thick aluminum laminae was smaller than that of its aluminum laminae.

For H type, the stress distribution in cross section of laminated composite beam was estimated from each breaking strain and stress-strain curve, and then the breaking stress was calculated from the sum of the resistance moment of stress (bending moment at the time when the composite beam breaks). The measured values were 0.50~0.58 times the calculated ones. For V type, the breaking stress can be expressed as $\sigma_1 v_1 + \sigma_2 v_2$; σ_1 and σ_2 are the stresses generated in aluminum and sugi wood respectively when the composite laminated beam breaks. v_1 and v_2 are the volume fractions of aluminum and sugi wood. Unlike H type, V type had the measured values very close to the calculated ones.

This is considered to be due to the effect of the deflection caused by shear force and the slippage of glue line by horizontal shear force were much greater in H type than in V type.

Kato et al. reported that the slippage of glue line caused by horizontal shear force occurred in the horizontally laminated wood beams glued with a synthetic rubber adhesive [10].

Most of H type including aluminum laminae 1mm thick fractured owing to the buckling of compression side of aluminum and the fracture of H type including aluminum laminae 2mm or 3mm thick occurred in the glue line of sugi wood with low shear strength. The fracture of V type was generated in the tensile side of sugi wood by bending moment.

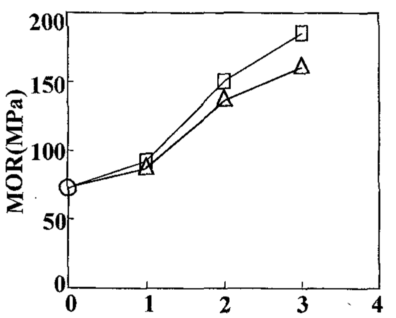

Fig. 6. Relation between MOR and aluminum lamina thickness for wood-aluminum laminated composite beams.
Legend : □ : H type, △ : V type, ○ : Sugi wood.

3.4 Specific bending modulus of elasticity and specific bending modulus of rupture

The specific MOEs (MOE/specific gravity, SMOE) and specific MORs (MOR/specific gravity, SMOR) for aluminum alloys, sugi wood and wood-aluminum laminated composite beams are shown in Table 2.

Sugi wood had a little lower value of SMOE than aluminum alloys. The SMOE of wood parallel to the grain is known to be comparable to that of metal.

Table 3. Specific modulus of elasticity and specific modulus of rupture for aluminum alloy, sugi wood and wood-aluminum laminated composite beams.

Type	T (mm)	Density (Mg/m^3)	SMOE (GPa)	SMOR (MPa)
Al	1	2.78	28.3	106
	2	2.72	28.2	199
	3	2.72	26.1	197
Sugi		0.392	25.3	185
H	1	0.646	28.5	143
	2	0.853	34.9	176
	3	1.06	33.1	174
V	1	0.653	20.7	133
	2	0.862	22.5	158
	3	1.06	22.3	151

Note : *T* : Thickness of aluminum lamina, SMOE : MOE/specific gravity, SMOR : MOR/specific gravity.

H type showed higher values of SMOE than aluminum alloys, but the SMOEs of V type were much lower than that of sugi wood. There was little influence of aluminum lamina thickness on those values.

The SMOR of sugi wood was markedly higher than that of aluminum 1mm thick, and was comparable to those of aluminum 2mm and 3mm thick. The SMOR of wood parallel to the grain is known to be markedly higher than that of steel, and to be comparable to aluminum alloy. The SMORs of H type including aluminum laminae 2mm and 3mm thick were slightly lower than that of sugi wood, but that of H type including aluminum laminae 1mm thick was lower than that of sugi wood. The SMORs of V type were lower than those of H type. The densities of laminated composite beams were 0.23~0.38 times that of aluminum alloy as shown in Table 3.

It was found that a material with a relatively low density and very high bending strength performances can be manufactured by laminating aluminum alloy laminae on sugi wood beam.

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