J Wood Sci (2012) 58:369–372
DOI 10.1007/s10086-012-1251-0

NOTE

A novel method for the reinforcement of harp soundboard

**Takuya Gunji · Eiichi Obataya · Hidefumi Yamauchi ·
Kenzo Aoyama**

Received: 11 October 2011 / Accepted: 18 January 2012 / Published online: 23 February 2012

Abstract The effects of a carbon fiber-reinforced plastic (CFRP) overlay on the wooden soundboard of a harp were compared to those of conventional veneer reinforcement with respect to the vibrational properties and bending strength. CFRP reinforcement has a minimal effect on the vibrational properties of the soundboard in its width direction, whereas conventional veneer reinforcement significantly reduces the acoustic conversion efficiency of the soundboard. The CFRP-reinforced soundboard also has sufficient bending strength in its longitudinal direction. These results indicate that CFRP is a promising material for the reinforcement of the wooden soundboards of harps to minimize the reduction of the sound amplitude.

Keywords Carbon fiber · Reinforcement · Soundboard · Vibrational properties · Bending strength

Introduction

A grand harp is a large stringed instrument equipped with a tall, wide wooden soundboard. The conventional structure of soundboards is shown in Fig. 1a. The soundboard is usually overlaid with a thin veneer whose fiber direction aligned to the radial direction of the base wood. Due to this plywood-like structure, cracks and splits in the base wood are effectively prevented by the overlaid veneer, which reinforces the longitudinal direction of the soundboard, i.e., the weak radial direction of the base wood. However, the veneer reduces the amplitude of sound by damping the flexural vibration of soundboard in its width direction. This adverse effect is due to the smaller specific dynamic Young's modulus (E'/ρ) and greater internal friction (Q^{-1}) of veneer and adhesive resin than those of base wood [1].

To reinforce the harp soundboard with minimal reduction in the amplitude of sound, we propose a novel method that incorporates a uniaxially oriented carbon-fiber composite (CFRP), as illustrated in Fig. 1b. In this structure, the longitudinal direction of the soundboard is reinforced by a thin CFRP sheet instead of overlaid veneer in conventional structure. Furthermore, the CFRP surface is overlaid with a thin veneer for esthetic reasons: a wood appearance is more acceptable for musicians than that of CFRP. Since the overlaid veneer does not need to reinforce the soundboard, its fiber direction is aligned in the width direction of the soundboard, i.e., the fiber direction of the base wood, for minimal reduction in the acoustic conversion efficiency. In this paper, we describe the vibrational properties and bending strength of CFRP-reinforced wood to confirm the potential of CFRP as an improved reinforcement material for harp soundboards.

Materials and methods

Conventional reinforcement using veneers

Sitka spruce wood (*Picea sitchensis*) was used as the base wood. A thinly sliced veneer (0.8 mm) was attached to the

T. Gunji · E. Obataya (✉)
Graduate School of Life and Environmental Sciences,
Tsukuba University, Ibaraki 305-8572, Japan
e-mail: obataya.eiichi.fu@u.tsukuba.ac.jp

H. Yamauchi
Institute of Wood Technology, Akita Prefectural University,
Akita 016-0876, Japan
e-mail: hide@iwt.akuta-pu.ac.jp

K. Aoyama
Aoyama Harp Company, Fukui 910-1127, Japan
e-mail: fukui@aoyama-harp.co.jp

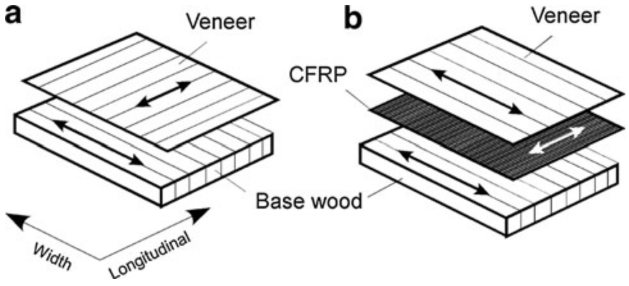

Fig. 1 Fiber alignment of **a** conventional veneer-reinforced soundboard and **b** CFRP-reinforced soundboard

edge grain surface of a Sitka spruce wood board (3–10 mm thick) with honeymoon-type glue (Konishi Co. HB10), which is generally used for harp making. To maintain consistency with the conventional structure of harp soundboards (Fig. 1a), the fiber direction of the veneer was aligned perpendicular to that of the base wood. First, a curing agent was applied (50 g/m^2) to the surface of the base wood and maintained at 25°C and 60% relative humidity (RH) for 1 day to allow the solvent to evaporate. Next, base resin was applied (100 g/m^2) to the surface of the veneer using a hand roller. Finally, the veneer was attached to the base wood and cured at room temperature for 1 h under a pressure of 0.1 MPa. The amount of glue was controlled by weighing the specimens before and after the application of glue as detailed in a previous article [1].

Reinforcement using CFRP

Sitka spruce wood boards were reinforced with CFRP and then overlaid with thin veneer, as shown in Fig. 1b. First, an uncured CFRP sheet (Toray Co., TORAYCA Prepreg P3051S-5, 60 µm thick) was attached to the surface of the veneer and compressed (0.5 MPa) at 150°C for 15 min. Neat epoxy resin in the CFRP acted as the glue for this step. Next, an epoxy glue (Konishi Co. E206S) was applied (100 g/m^2) to the surface of the CFRP and left at room temperature for 2 h. Finally, the veneer-CFRP composite was applied to a wood board and compressed (1 MPa) at room temperature for 20 h.

Wood specimens

Unreinforced, veneer-reinforced, and CFRP-reinforced wood boards were cut into strips with dimensions of 200 mm (L, along the fiber direction of the base wood) × 15 mm (R, along the radial direction of the base wood). These strips, which represent the width direction of the harp soundboard, were subjected to vibration measurements. In addition, strips with dimensions of 100–150 mm (R) × 15 mm (L) were made and used to evaluate the strength of the soundboard in its longitudinal direction, i.e., the R direction of the base wood. All specimens were conditioned at 25°C and 60% RH for at least 1 month prior to the mechanical tests, and 18 specimens were employed for each testing condition.

Preparation of CFRP and resin plates

To determine the vibrational properties of CFRP, ten uncured CFRP sheets were stacked with their fiber directions aligned. The resultant CFRP plate was cured at 150°C for 15 min under 6.5 kPa of pressure and cooled to room temperature under compression. The plate was then cut into strips with dimensions of either 100 mm (fiber direction) × 15 mm (perpendicular to fiber direction) × 0.5 mm or 100–150 mm (perpendicular to fiber direction) × 15 mm (fiber direction) × 0.5 mm. Meanwhile, epoxy glue was spread onto a flat polytetrafluoroethylene plate and cured at room temperature. The resultant plate was then cut into strips with dimensions of 10 × 80 mm.

Vibrational measurements

The specific dynamic Young's modulus (E'/ρ) and internal friction (Q^{-1}) of the wood, CFRP, and resin plate samples were determined at 25°C and 60% RH using the free flexural vibration method [2]. The setup of equipments and detailed procedure are described in a previous article [1]. The E'/ρ and Q^{-1} values were calculated from the resonance frequency of the first mode vibration and width of the resonance curve, respectively. The resonance frequency ranged from 300 to 1,500 Hz.

Bending tests

The bending strength of the specimens was measured using a three-point bending test. The effective span was 80 mm and the crosshead speed was 10 mm/min. The specimens were settled during the straining of their reinforced surfaces.

Results and discussion

Vibrational properties of CFRP-reinforced wood

Figure 2 shows the relative E'/ρ and Q^{-1} values of reinforced wood plotted against the thickness of the base wood (t_0). Conventional veneer reinforcement resulted in a significant reduction in E'/ρ and increase in Q^{-1} particularly when thinner base wood was used. This is predicted to reduce the amplitude of sound because it has been proven both theoretically and experimentally that a greater acoustic conversion efficiency (i.e., $\sqrt{E'/\rho^3}/Q^{-1}$) is

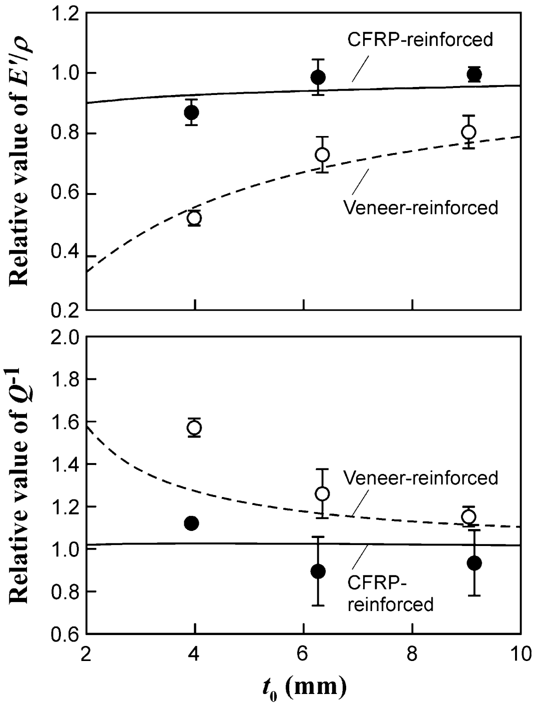

Fig. 2 Relative values of the specific dynamic Young's modulus (E'/ρ) and internal friction (Q^{-1}) plotted against the thickness of the base wood (t_0). The *open and filled plots* represent the experimental data for veneer-reinforced and CFRP-reinforced wood, respectively. The *dashed and solid lines* represent the results of the calculations using a multi-layered model for veneer-reinforced and CFRP-reinforced wood, respectively [1]. The *bars* indicate standard deviations

essential for increased sound radiation amplitude [3, 4]. In contrast, CFRP reinforcement had a minimal impact on the E'/ρ and Q^{-1} values. This suggests that CFRP reinforcement is superior to conventional veneer reinforcement with respect to sound amplitude.

Using the multi-layered model that was proposed in a previous paper [1], we calculated the vibrational properties of reinforced wood that comprised base wood, a glue layer, and a reinforcement layer. Table 1 lists the basic parameters used for the calculations. The results of calculation are represented as lines in Fig. 2. Considering the simplicity of the model, the agreement between the calculated and experimental values was fairly good.

As suggested in a previous paper [1], the significant reduction in E'/ρ and increase in Q^{-1} due to conventional veneer reinforcement are mainly due to the smaller E'/ρ and greater Q^{-1} values of veneer in the R direction. Probably the sound amplitude can be improved by using thinner veneer, but this results in reduced strength of the soundboard in its longitudinal direction. This dilemma cannot be solved using wood veneer as a reinforcement material.

Similar to wood veneer, CFRP is an anisotropic material; its smaller E'/ρ and greater Q^{-1} (perpendicular to fiber direction) values are also predicted to degrade the amplitude of sound. Therefore, the CFRP is not expected to improve the acoustic quality of the soundboard from the beginning, when its fiber direction is aligned in the longitudinal direction of the soundboard. However, the CFRP layer is much thinner than the base wood and therefore it has a minimal effect on the vibrational properties of the soundboard. Additionally, the veneer overlaid on the CFRP-reinforced wood does not affect the vibrational properties of the base wood because its fiber direction is aligned parallel to that of the base wood. Consequently, the vibrational properties of CFRP-reinforced wood are almost the same as those of unreinforced wood. That is, the CFRP functions as a reinforcement while its artificial appearance and adverse acoustic impact are "blinded".

Table 1 Characteristics of the tested wood and CFRP

	ρ (kg/m^3)	E' (GPa)	Q^{-1}
Wood			
L direction	420	14.3	0.0068
R direction		0.936	0.0206
CFRP			
Along fiber	1,428	82.6	0.0022
Perpendicular to fiber		6.8	0.0081
Adhesives			
Honeymoon-type glue[a]	1,200	2.6	0.189
Epoxy glue[b]	1,114	2.6	0.042

[a] Used in conventional veneer-reinforcement[1]

[b] Used for the adhesion of CFRP and wood

Bending properties

The bending strength of a soundboard in the longitudinal direction is important because this direction corresponds to the weak R direction of the base wood. To compare the reinforcement imparted by veneer and CFRP, their relative maximum bending load ($P_{\max}$) values are plotted against t_0 in Fig. 3. The $P_{\max}$ values of the reinforced specimens were normalized with that of an unreinforced specimen. The results revealed that the $P_{\max}$ of the reinforced wood is twice that of unreinforced wood. For thin base wood ($t_0 < 4$ mm), CFRP reinforcement is less effective than conventional veneer reinforcement; however, this is not a significant problem because serious cracks in harp soundboards usually occur in the thicker middle part ($t_0 > 4$ mm). In the thicker part, the effect of CFRP reinforcement is comparable to that of conventional veneer reinforcement. This proves that CFRP reinforcement sufficiently supports the tensile force of the strings.

In Fig. 4, the bending load (P)-deflection curves of reinforced specimens are compared to that of an unreinforced specimen. Regardless of the reinforcement material,

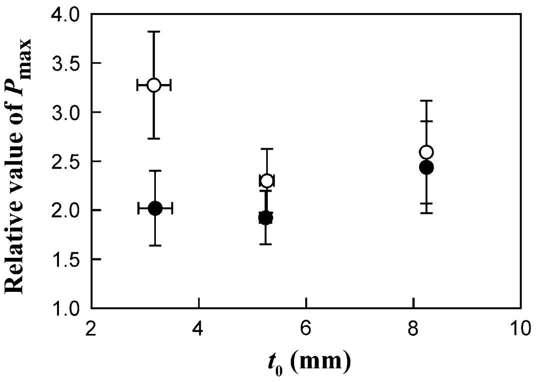

Fig. 3 Relative values of maximum bending load (P_{max}) as a function of t_0. The *symbols* are the same as those in Fig. 2. *Bars* indicate standard deviations

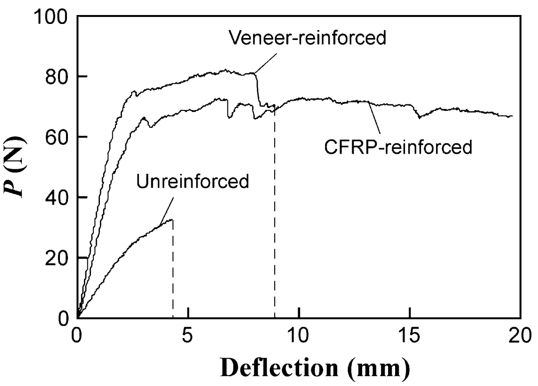

Fig. 4 Bending load (P)-deflection curves

the reinforced wood did not exhibit a clear breaking point and successfully supported a large bending load. This ductile nature of reinforced wood is explained by the compressive deformation of the unreinforced back surface. With respect to ductility, the effect of CFRP reinforcement was comparable to that of conventional veneer reinforcement.

Strictly speaking, the overlaid veneer is not necessary in the CFRP-reinforced structure. However, the wood appearance imparted by the overlaid veneer must be more acceptable for musicians than that of CFRP. The appearance of the CFRP-reinforced soundboard is different from that of conventionally veneer-reinforced one in respect of their fiber directions, but such a difference is not a problem because the fiber direction of harp soundboard is originally aligned in its width direction. In this sense, the CFRP-reinforced soundboard looks “traditional” rather than modern veneer-reinforced soundboard.

Conclusions

In contrast to the significant reduction in E'/ρ and increase in Q^{-1} caused by conventional veneer reinforcement, CFRP reinforcement had a minimal impact on the vibrational properties of wood. CFRP sufficiently improves the bending strength of the radial direction of wood, which corresponds to the longitudinal direction of a harp soundboard. These results indicate that CFRP reinforcement is a promising method to improve the mechanical and acoustic properties of harp soundboards. Further sensory evaluation is required to prove the practical performance of CFRP-reinforced soundboards.

References

1. Gunji T, Obataya E, Aoyama K (2011) Vibrational properties of harp soundboard with respect to its multi-layered structure. J Wood Sci. doi:10.1007/s10086-012-1253-y
2. Hearmon RFS (1958) The influence of shear and rotary inertia on the free flexural vibration of wooden beams. J Appl Phys 9:381–388
3. Yano H, Matsuhisa H (1991) Study on the timber of wood II, analysis of the sound spectrum of wood using viscoelastic Timoshenko equation. Scientific Reports of the Kyoto Prefectural Univ. 43:24–31
4. Ono T (1996) Frequency responses of wood for musical instruments in relation to the vibrational properties. J Acoust Soc Jpn (E) 17:183–193