ARCHIVES OF ACOUSTICS
4, 4, 305-316 (1979)

INVESTIGATIONS ON A POSSIBLE SUBSTITUTION OF RESONANT WOOD IN PLATES OF MUSICAL INSTRUMENTS BY SYNTHETIC MATERIALS*

D. HOLZ

Institut für Musikinstrumentenbau (DDR — 9657 Zwota)

Since resonant plates in stringed musical instruments are made from coniferous woods, particularly from spruce, with maximum quality requirements, investigations were carried out in order to test the use of other materials for this purpose. These were aluminium plates with two types of visco-elastic layer, and laminates of glass fibre reinforced epoxy and unsaturated polyester resin, with reinforcements of several types, but preferably unidirectional fibres. The conclusions resulting from the measured data of sound velocity and damping in the audible frequency range only encourage further research upon laminates of glass fibre reinforced plastics.

1. Introduction

As is well known, customary musical instruments with strings need radiating or resonant plates, e.g. the soundboard in a piano or the top plate in a violin or guitar. In some previous papers it was demonstrated [2, 3] that the acoustic efficiency of radiating plates depends on their bending stiffness, conditions of radiation, velocity and resistance of bending waves, mass per unit area, and damping.

These correlated magnitudes are referred to material qualities such as the modulus of elasticity E, the density ϱ, and the damping factor η', and to the dimensions of the plate, particularly the thickness. The value η' is defined by

$$\eta' = \frac{\Lambda}{\pi} = \frac{\Delta f}{f_R},$$

where Λ is the logarithmic damping decrement, f_R — the eigenfrequency in Hz, and Δf — the half power width.

---

* The first version of this paper was presented at the 22nd Open Seminar on Acoustics in Świeradów Zdrój, Poland, September 1975.

For optimally resonant wood a high E, a ϱ as low as possible, and a damping intermediate between those of metals and plastics, are demanded.

Such qualities agree with the rule that spruce, and perhaps a few other coniferous woods marked by specific parameters, are not only the best but possibly the sole materials for normal radiating plates. This is a due to the anisotropy of spruce and of woods in general, where the above-mentioned qualities are realized only along the grain (i.e. the fibre direction or beam axis), whereas perpendicular to the grain E is significantly smaller and η' is higher than the corresponding values for several other materials, including a number of plastics.

Frequently in the literature a high ratio for E/ϱ^3 called the acoustic constant or musical constant, is demanded, although some wood types as Balsa (Ochroma lagopus) or parasolier (Musanga smitthii), which have a very small density and thus a high "acoustic constant", have never been used or accepted as resonant wood. It was stressed in our previous work that the value of this ratio, claimed by Hörig [4] as "Strahlungsdämpfung" $\vartheta_s = 5\cdot 10^{-8}\sqrt{E/\varrho^3}$ with omitted dimensions, is often overestimated, and that E/ϱ (or its square root, the sound velocity in bars) is particularly important for characterizing resonant wood. Thus interest should be taken in using other woods with a high E/ϱ and a lower E/ϱ^3. However, the decreasing supply of high-grade resonant wood in the world will, in the future, not correspond to its demand for the increasing production of musical instruments. Thus we have been involved in a search for other materials, in order to prepare a possible substitute for resonant wood in musical instruments in industrial production. There was no idea of using new materials in instruments manufactured by craftsmen.

2. Survey of possible substitutes

In looking for suitable substituting materials Figs. 1 and 2 may be considered useful. In Fig. 1 the relation between ϱ and E is shown for some groups of materials. Two straight lines have been drawn in this diagram: the line for all data of the important sound velocity $c_D = 5000\,\mathrm{m/s}$ and that for a high resonance ratio $Q_R = \sqrt{E/\varrho^3}$ of 10 $\mathrm{m^5/Ns^3}$ (we proposed this definition instead of "acoustic constant", which is only a quotient with omitted dimensions). Obviously such a high resonance ratio is valid only for a few woods; it is indeed even exceeded by few wood types such as those mentioned above but no other material can attain it.

A sound velocity of about 5000 m/s is given for several metals, such as iron, iridium, magnesium, and aluminium, and also for glass, porcelain, and, of course, for a number of woods. None of these materials, with the exception of wood, meets the condition of intermediate damping (Fig. 2). From this diagram it is evident that no individual, homogeneous material is suitable

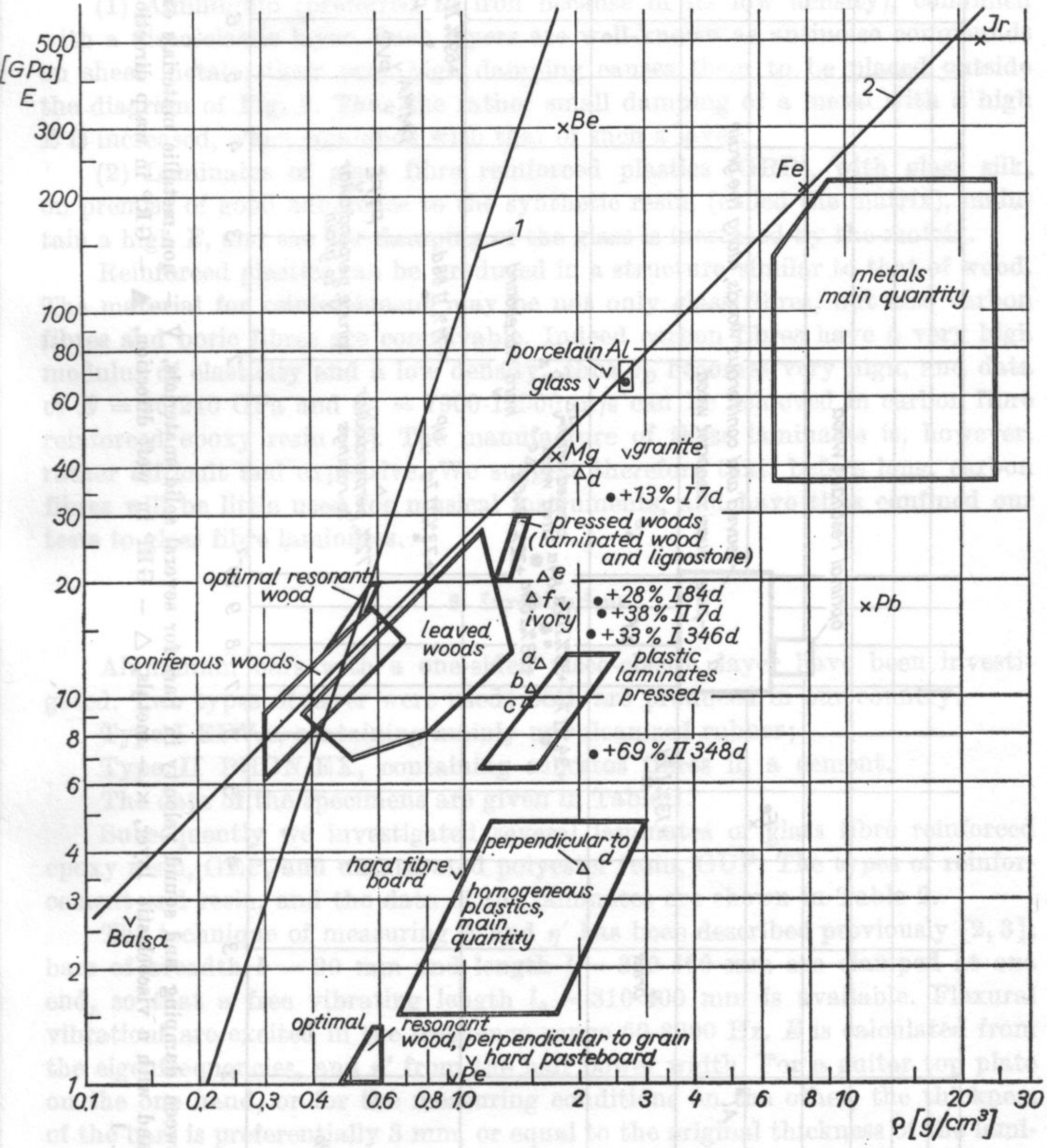

Fig. 1. Relation between density and modulus of elasticity for several solid metarials, V — non-metalic materials except GRP, ● — aluminium only and with a visco-elastic layer, according to Table 1, x-metals, △ — glass fibre reinforced plastics (GRP), according to Table II; 1 — $Q_R = \sqrt{E/\varrho^3} = 10\ \mathrm{m^5/Ns^3}$, 2 — $c_D = 5\,000$ m/s; glass fibre proportion and direction: (*a*) 55.7 % weft, (*b*) 29.4 % indifferent, (*c*) 45.4 % weft, (*d*) 72.0 %, rovings, (*e*) 55.7 % warp preferred, (*f*) 45.4 % warp preferred

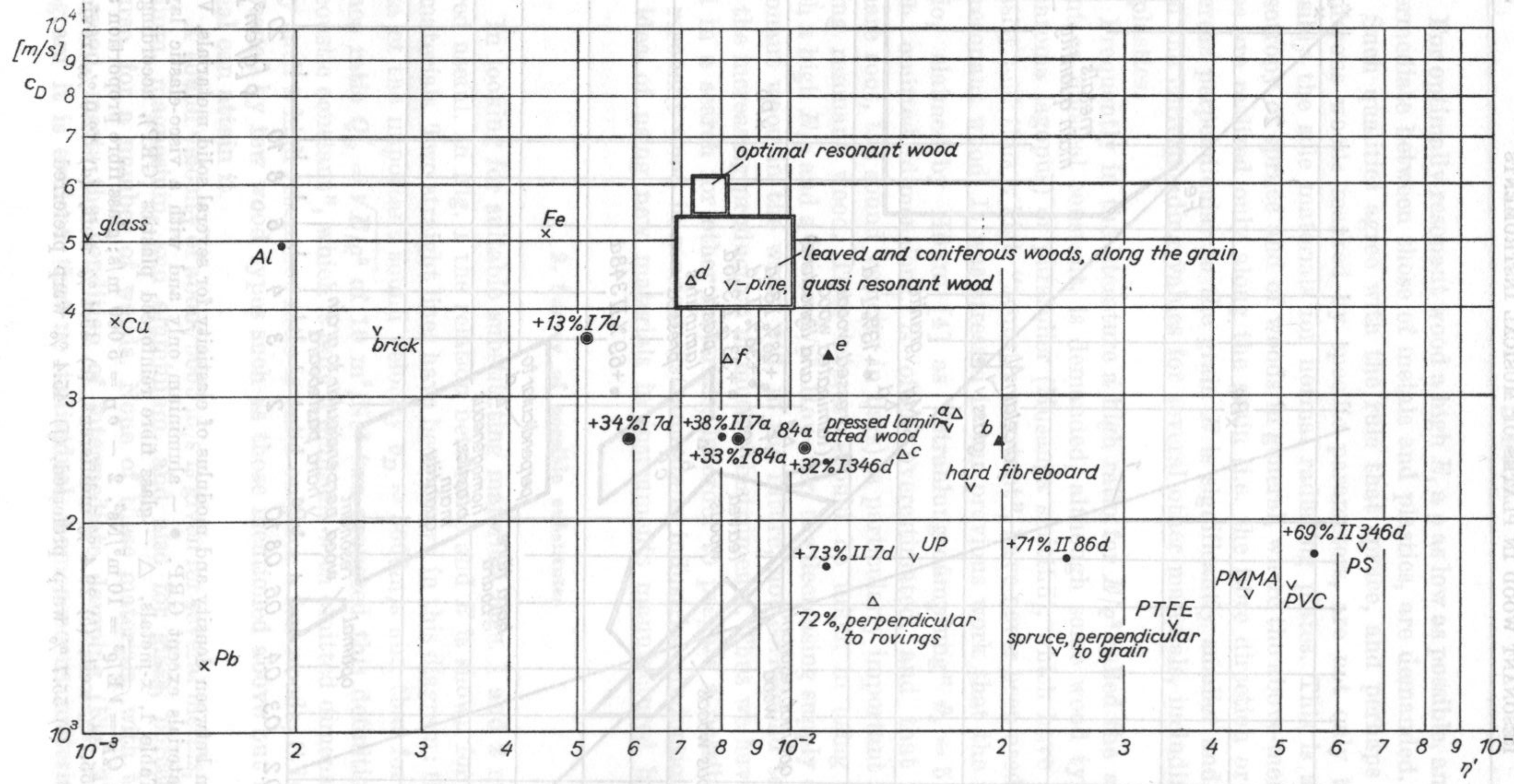

Fig. 2. Relation between damping and sound velocity in bars for several solid materials, V — non-metallic materials except GRP, ⊙ — aluminium only and with a viscoelastic layer, × — metals, △ — GRP in weft direction, ▲ — GRP in warp direction or preferred, a-f according to Fig. 1

for the substitution of resonant wood, but it appears possible to find a combination of two different materials. Two composite materials may be principally considered:

(1) Aluminium (preferred to iron because of its low density), combined with a visco-elastic layer. Such layers are well-known as antinoise compounds on sheet metals; their very high damping causes them to be placed outside the diagram of Fig. 2. Thus the rather small damping of a metal with a high E is increased, when combined with that of such a layer.

(2) Laminates of glass fibre reinforced plastics (GRP), with glass silk, on premise of good adherence to the synthetic resin, (called the matrix), maintain a high E, and the low damping of the glass is increased by the matrix.

Reinforced plastics can be produced in a structure similar to that of wood. The material for reinforcement may be not only glass fibres, but also carbon fibres and boric fibres are conceivable. Indeed carbon fibres have a very high modulus of elasticity and a low density, thus c_D becomes very high, and data of $E = 96\text{-}240$ GPa and $c_D = 7900\text{-}12500$ m/s can be achieved in carbon fibre reinforced epoxy resin [1]. The manufacture of these laminates is, however, rather difficult and expensive. We suggest therefore that, before long, carbon fibres will be little used for musical instruments, and have thus confined our tests to glass fibre laminates.

3. Investigations

Aluminium bars with a one-sided visco-elastic layer have been investigated. Two types of layer were used; both are produced in our country:

Type I EIWA, containing mainly unvulcanized rubber;

Type II PHON-EX, containing asbestos fibres in a cement.

The data of the specimens are given in Table 1.

Subsequently we investigated several laminates of glass fibre reinforced epoxy resin, GEP, and unsaturated polyester resin, GUP. The types of reinforcement and resin, and the data of the laminates are shown in Table 2.

The technique of measuring E and η' has been described previously [2, 3]; bars of breadth $b = 20$ mm and length $l = 350\text{-}460$ mm are clamped at one end, so that a free vibrating length $l_0 = 310\text{-}400$ mm is available. Flexural vibrations are excited in the frequency range 60-8000 Hz. E is calculated from the eigenfrequencies, and η' from the half power width. For a guitar top plate on the one hand, or for the measuring conditions on the other, the thickness of the bars is preferentially 3 mm, or equal to the original thickness of the laminate.

In view of the anisotropy of the laminates the bars were sawn in both warp and weft directions, i.e. in the direction of the rovings and perpendicular to it, respectively. The direction of the higher E is called the preferred or main direction. Results from the 2nd until the 24th eigenfrequency were obtained.

Table I. Aluminium bars with a layer of visco-elastic material for increase of damping

Material	Layer mass [%]	Specimen thickness [%]	Aging after coating d	Sound velocity [m/s]
aluminium only	0	3.0 mm = 100	—	4950
coated by EIWA (I)	13	125	7	3630
	34	165	7	2510
	33	163	84	2440
	32	162	346	2550
	28	155	7	2730
	28	153	84	2800
	38	159	7	2640
coated by Phon-Ex (II)	73	213	7	1740
	71	210	86	1770
	69	208	348	1790

Table II. Structure of investigated GRP-plates and GRP-bars

Designation	Resin type	Reinforcement material (E-glass), type	Glass mass [%]	Efficiency in warp (main) direction [%]
GRP – UP (GUP)	polyester	thin orthotropic* glass silk tissues, outwards; rude roving tissues, preferred in warp direction, inwards	55.7	85.5
GRP – EP (GEP)	epoxy	thin orthotropic glass silk tissues, outwards; rude roving tissues, preferred in warp direction, inwards	45.4	84.7
GUP	polyester	chopped strand mat, quasi isotropic	29.4	50
GUP	polyester	rovings only, unidirectional	72.0	100

* Orthotropic tissue, i.e. quadratic tissue quantities warp strings as much as weft strings.

Up to 2500 Hz not only flexural vibrations, but also some peaks of torsional vibrations and of quasilogitudinal waves were registered. From Fig. 3 it is obvious that the vibration nodes of such frequencies can be shown using Lycopodium spores. Symmetrical curves are attained by flexural waves, see $f_R = 384$ Hz.

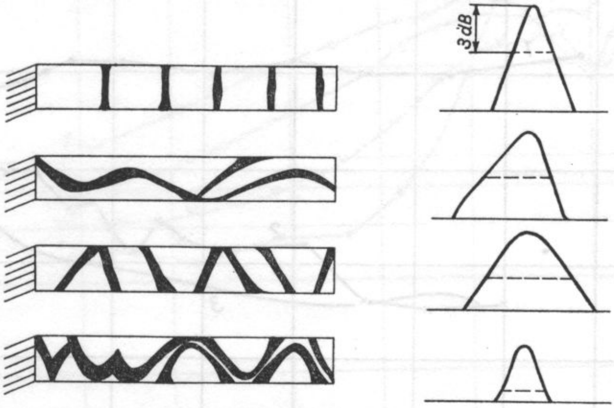

Fig. 3. Illustration of some different vibration nodes, by Lycopodium spores, and of their resonance curves (sole bending wave) : 1 – $f_R = 384$ Hz, 2 – $f_R = 480$ Hz, 3 – $f_R = 630$ Hz, 4 – $f_R = 2100$ Hz

4. Results

In all investigations the damping depends on the frequency (in the audible frequency range). As expected, the damping of aluminium with a visco-elastic layer increases, as the layer thickness increases. Due to the very low E of the layer compound itself, the E of the composite material decreases, as the layer thickness increases, and the sound velocity also diminishes. These results are seen in Figs. 1 and 2.

In principle a damping can be attained which closely approximates that of wood in any frequency range. This can be achieved by optimizing the layer thickness according to the type and properties of the layer compound. The dependence of damping upon frequency, Fig. 4, is nevertheless different from that of resonant wood. This fact is not as remarkable as the influence of aging upon damping. From Fig. 4 it is evident that η' varies over a period of time of nearly one year, not only as a result of drying but also because of aging of the visco-elastic material. It is probable that the age effects will last for at least two years.

In Fig. 5 the dependence of damping for GRP laminates is compared with that for resonant spruce along the grain. As is evident from Fig. 5a, rein-

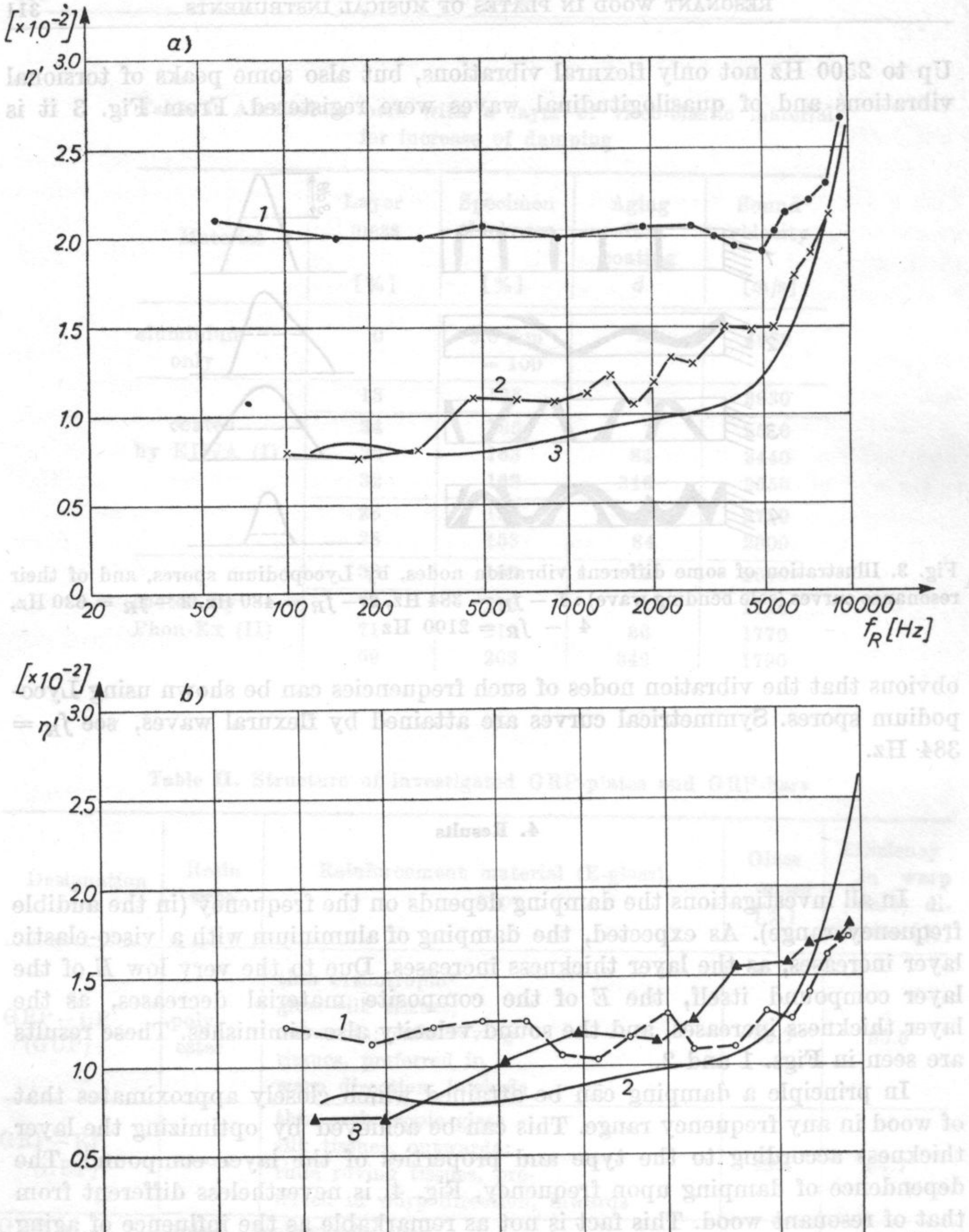

Fig. 4. Dependence of damping on frequency for glass fibre reinforced plastics: (a) epoxy resin (GEP), 1 — GUP, mat, glass 29,4 %, 2 — GUP in warp direction, tissue, glass mass 45.4 %, 3 — resonant spruce along the grain, (b) with PHON-EX (II), 1 — GUP, in warp direction, tissue, glass mass 55.7 %, 2 — resonant spruce along the grain, 3 — GUP in rovings direction, rovings only, glass mass 72 %.

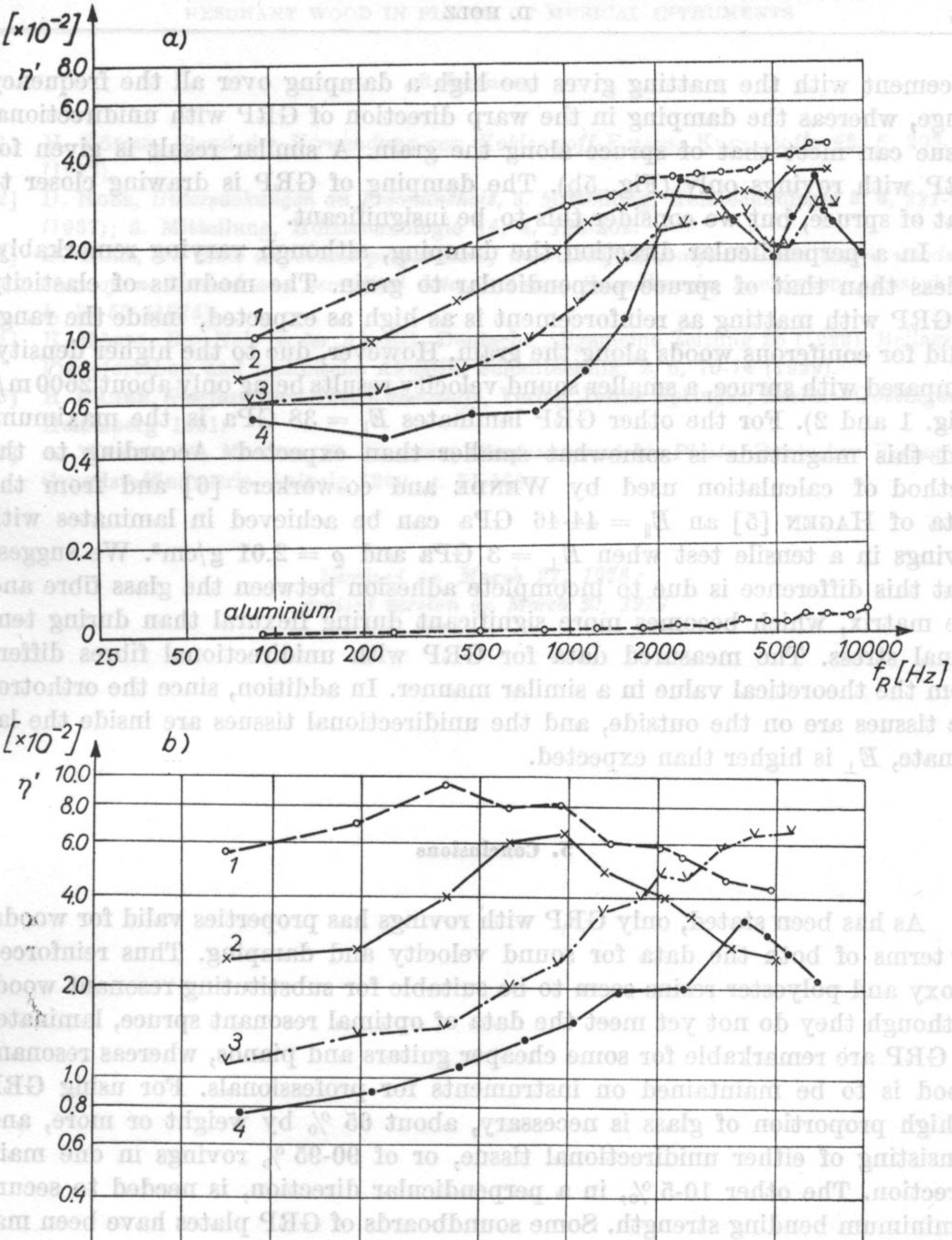

Fig. 5. Dependence of damping on frequency for aluminium only and with a visco-elastic layer, before and after natural aging at room temperature: (a) with EIWA (I) 1 − +31 %/346 d, 2 − +31 %/84 d, 3 − +31 %/7 d, 4 − +13 %/7d; (b) unsaturated polyester resin (GUP), 1 − +31 %/346 d, 2 − +71 %/86 d, 3 − +73 %/7d, 4 − 38 %/7d

forcement with the matting gives too high a damping over all the frequency range, whereas the damping in the warp direction of GRP with unidirectional tissue can meet that of spruce along the grain. A similar result is given for GRP with rovings only (Fig. 5b). The damping of GRP is drawing closer to that of spruce, but we consider this to be insignificant.

In a perpendicular direction the damping, although varying remarkably, is less than that of spruce perpendicular to grain. The modulus of elasticity of GRP with matting as reinforcement is as high as expected, inside the range valid for coniferous woods along the grain. However, due to the higher density, compared with spruce, a smaller sound velocity results being only about 2600 m/s (Fig. 1 and 2). For the other GRP laminates $E_{\parallel} = 38$ GPa is the maximum, and this magnitude is somewhat smaller than expected. According to the method of calculation used by WENDE and co-workers [6] and from the data of HAGEN [5] an $E_{\parallel} = 44$-46 GPa can be achieved in laminates with rovings in a tensile test when $E_{\perp} = 3$ GPa and $\varrho = 2.01$ g/cm³. We suggest that this difference is due to incomplete adhesion between the glass fibre and the matrix, which becomes more significant during flexural than during tensional stress. The measured data for GRP with unidirectional fibres differs from the theoretical value in a similar manner. In addition, since the orthotropic tissues are on the outside, and the unidirectional tissues are inside the laminate, $E_{\perp}$ is higher than expected.

5. Conclusions

As has been stated, only GRP with rovings has properties valid for woods, in terms of both the data for sound velocity and damping. Thus reinforced epoxy and polyester resins seem to be suitable for substituting resonant wood. Although they do not yet meet the data of optimal resonant spruce, laminates of GRP are remarkable for some cheaper guitars and pianos, whereas resonant wood is to be maintained on instruments for professionals. For using GRP a high proportion of glass is necessary, about 65 % by weight or more, and consisting of either unidirectional tissue, or of 90-95 % rovings in one main direction. The other 10-5 %, in a perpendicular direction, is needed to secure a minimum bending strength. Some soundboards of GRP plates have been manufactured and tested. Their sound levels in the frequency range of interest and their decay behaviour are similar to those of normal spruce soundboards.

On the other hand, further investigation on metals with visco-elastic layers seems to be unpromising. This is due mainly to the great influence of aging upon the damping, which cannot be predetermined, and also by the very small modulus of elasticity of the layer material. This behaviour does not meet the demands of quality for any radiating plate.

References

[1] H. Böder, *Stand der Verwendung von Kohlenstoff-Fasern*, Kunststoffe **62**, 5, 293-296 (1972).

[2] D. Holz, *Untersuchungen an Resonanzholz*, 3. Mitteilung, Holztechnologie **8**, 4, 221-224 (1967); 5. Mitteilung, Holztechnologie **14**, 4, 195-202.

[3] D. Holz, *On some important properties of non-modified coniferous and leaved woods in view of mechanical and acoustical data in Piano Soundboards*, Archiwum Akustyki **9**, 1, 37-57 (1974).

[4] H. Hörig, *Das Holz in der Akustik*, Deutsche Allgemeine Zeitung 25 (1929), Beilage – Pianofortebau und technische Akustik, Schalltechnik, **2**, 5, 70-74 (1929).

[5] H. Hagen, *Glasfaserverstärkte Kunststoffe*, Verlag Julius Springer, Berlin – Göttingen – Heidelberg 1961.

[6] A. Wende, W. Moebes, H. Marten, *Glasfaserverstärkte Plaste*, Deutscher Verlag für Grundstoffindustrie, Leipzig 1969, p. 71-180.

Received on March 27, 1978;
revised version on March 30, 1979