VARNISH1.DOC

ON VARNISH

SUMMARY

A theoretical approach to the stiffening of spruce plates by varnishing with thin layers of natural resins suggests that the longitudinal stiffness is always reduced. The transverse stiffness will be increased.

Adding particulate reinforcing to the varnish layer requires large amounts to restore the longitudinal stiffness to that of the unvarnished spruce but adds greater stiffness in the transverse direction. There is some support in the literature.

INTRODUCTION

A discussion of varnish in the context of the violin invokes thoughts of adding the final touch to the beauty of a new creation and hopefully that extra touch to the brilliance of the sound that will issue forth in the hands of a master. Much has been written about the importance of varnish to the quality of sound obtained by virtuoso players from violins made in the 17th and early 18th centuries even when large areas had been removed by wear and tear without affecting the performance of the maestro. The virtues of the original varnish were extolled and the secrets locked up in the now unknown formulae. Even the likelihood of instruments being reworked and revarnished have been ignored to maintain the myth.

That instrument values have risen dramatically reflects the growing rarity of artifacts that have become works of art and that some combine the rare quality that they make it easy for the

McLennan, J.E. (2000) "On varnish" Journal of Australian Association of Musical Instrument Makers, XIX (1) 16-27.

player to communicate to the listener, by way of the sounds he creates, the music he plays . To-day, players are more likely to take credit for the quality of the sound they make rather than attribute it entirely to the instrument once it has been chosen for what it can give the player by way of assistance.

The varnish serves to protect the violin from dirt and moisture as a working instrument and to enhance the beauty of the wood. Wood being cellular, when cut presents an open surface which is easily soiled and affected by moisture unless sealed with an impervious layer able to withstand the rigours of use. This varnish layer was kept as thin as possible and was not expected to modify the properties of the substrate. The idea of a surface layer enhancing the stiffness of wood became popular in an attempt to explain the performance of classical violins which had what was thought to be exceptionally thin top plates. The varnish was accredited with this role until it was realised that the violin was not affected when the varnish was worn off large areas. The mystery still remained because these so called "bare" areas remained clean and did not become soiled as did untreated wood.

The interest then moved to the sometime particulate layer beneath the varnish. It was long established that the wood required to be sealed to present a smooth uniform surface on which to apply the varnish and more importantly to prevent absorption of varnish into the surface layer of cells, especially uneven absorption as would occur at any exposed endgrain that is present on a carved top. Andrew Dipper [1] surveyed the use of mineral ground coatings as they have appeared in the historical literature.

The few samples of varnish that have been examined [2] have not led to any general conclusions. Particulate material has been found under the varnish layer and identified in some instances as an active silicate mineral of volcanic origin, from Pozzuoli, a village near Naples. It is not known how continuous the particulate layer was. It may have been the residue from a polishing operation.

Ways of intentionally stiffening a substrate with a surface layer rely on either choosing a layer that is stiffer than the substrate and applying an appropriate thickness or modifying the stiffness of the layer with some reinforcement. The reinforcement may be lamellar, fibrous or particulate. In the case of violins, a continuous lamellar form would be difficult in the context of a varnish layer. It would be more suited when designing the initial plate as was done with a carbon fibre/epoxy-cardboard sandwich [3]. Fibrous reinforcment could be in the form of lengths equal to the dimensions of the plate. Particulate reinforcement could be in the form of short fibres, irregular particles, spheres or small plates. A number of minerals have these forms, except that of spheres, with the exception of opals. Layers underneath the varnish must be transparent which rules out some possibilities. Most "fillers" in a crystalline state become transparent when added to a carrier liquid. A filler is often the first step in preparing a wood surface for varnish and also acts to isolate the varnish layer. Examples of the minerals in mind are glass (window) D = 2500 kg/m^3, calcium carbonate (limestone) D = 2700 kg/m^3, calcium sulphate (gypsum) D = 2320 kg/m^3, silica (quartz) D = 2650 kg/m^3 and mica D = 3000 kg/m^3. These minerals in commonly available forms and others such as ground glass have been used for a long time [4].

It is important when contemplating a particular reinforcing agent to anticipate what influence it might have on the stiffening effect intended. Some simple expressions are available that will allow a quantitative prediction of their usefulness. Beginning with a simple varnish layer applied to only one surface. We can distinguish between an oil varnish i.e. a resin dissolved in linseed oil all of which becomes the hardened layer, and a spirit varnish which is a resin dissolved in a solvent which evaporates leaving only the resin as the varnish layer. Schelleng [5] in a classic paper on the physical effect of varnish dealt with an oil varnish which he estimated had an elastic modulus of about 2.6 x 10^9 Pa. More recently Ono [6] measured the elastic modulus of a copal resin layer deposited from a solution in toluene as 3.6 x 10^9 Pa and represents a spirit varnish. These values lie between the longitudinal and radial elastic moduli of spruce.

DETERMINING VARNISH THICKNESS

It might be appropriate here to talk about determining the thickness of the varnish layer. It is most conveniently found by obtaining the increase in weight of the plate and using D = M/V. The area of the plate would have to be known. For a simple varnish layer the calculation is straight forward. The overall density of a varnish layer incorporating mineral particles is a little more involved and can be found from:

$$D = (1 - V_F)D_V + V_F D_M$$

where D is the density of the combined layer, D_V is the density of the varnish and can be assumed to be 1050 kg/m^3 , D_M the density of the mineral and V_F is the volume fraction of mineral present. This value is then used in determining the thickness.

THE STIFFNESS OF VARNISHED SPRUCE

The stiffness of a composite beam of spruce with a varnish layer on one surface can be taken as a starting point for our initial purpose. The total stiffness is the sum of contributions from the spruce and the varnish. It is assumed that the varnish layer is thin compared with the thickness of the spruce and that it is rigidly attached and deforms with the wood underneath. Following Scanlan [7] :

$$(EI)_T = (EI)_S + (EI)_V$$

where E is elastic modulus, I is the area moment of inertia and the subscripts refer to the materials being considered; T the total layer, S the spruce substrate, and V the varnish layer.

ONE VARNISH LAYER

I will consider the case of one varnish layer and the effect of adding a particulate filler which will act as a reinforcing agent. The limit when there is no filler will represent a simple varnish coat while 100% filler will represent a layer of the reinforcing mineral being used, however it might be applied.

The expression for the combined elastic modulus, from the above equation, becomes:

$$E_T = h^3/(h + t)^3[E_s + E_v(3t/h)]$$

where h is the "plate" thickness and t is the thickness of the varnish layer. If we take typical values for h (= 3 mm) and t (= 0.03 mm) this becomes: (see appendix)

$$E_T = 0.97059\ (E_s + 0.009\ E_s) = 0.9793\ E_s$$

where E_s is taken equal to E_L for spruce (= 10 x 10^9 Pa) and E_v is taken as equal to $0.3E_s$ (= 3 x 10^9 Pa).

If we now modify the varnish layer by adding a filler, we will get a different elastic modulus.

$$E_{vp} = V_pE_p + (1 - V_p)E_v \quad = [3V_p + 0.3(1 - V_p)]\ E_s$$

which gives a final expression for the spruce with the reinforced varnish:

$$E_{TP} = h^3/(h + t)^3\ [E_s + E_{vp}\ (3t/h)]$$

$$= \quad 0.97059\ (E_s + 0.03\ E_{vp})$$

for the values given above. E_{TP} is tabulated below for varying volume fractions of the filler particles and expressed in terms of E_L rather than E_s.

V_p	E_{vp}/E_L	E_{Tp}/E_L
0.0	0.30	0.9793
0.1	0.57	0.9872
0.2	0.84	0.9951
0.4	1.38	1.0108
0.6	1.92	1.0265
0.8	2.46	1.0422
1.0	3.00	1.0579

It can be seen that for the typical values given above that a plain varnish layer reduces the combined elastic modulus and that 30% filler is required to restore it to the unvarnished value for spruce along the grain.

The effect on the elastic modulus across the grain gives the results below expressed in terms of E_R (= 1 x 10^9 Pa)

V_P	E_{VP}/E_R	E_{TP}/E_R
0.0	3.0	1.0579
0.1	5.7	1.1366
0.2	8.4	1.2152
0.4	13.8	1.3724
0.6	19.2	1.5297
0.8	24.6	1.6869
1.0	30.0	1.8441

It can be seen that the varnish layer raises the effective elastic modulus across the grain marginally and that 30% raises it 20%. A continuous layer of the "filler" would nearly double it.

EFFECT OF VARIATION IN VARNISH THICKNESS

The equation for E_T viz. $E_T = h^2/(h + t)^2\ [E_s + E_V(3t/h)]$, can be used to explore the effect of variation in varnish thickness, t. Using the numbers for E_L, E_R, and E_V above we get the values listed in the following table for variation in t.

t	$h^2/(h + t)^2$	$E_T(=E_L)$	$E_T(=E_R)$
0.0	1.0000	1.000 E_L	1.000 E_R
0.01	0.9900	0.993	1.012
0.02	0.9803	0.986	1.039
0.03	0.9706	0.979	1.058
0.04	0.9610	0.973	1.076
0.06	0.9423	0.959	1.112
0.08	0.9241	0.946	1.146
0.10	0.9063	0.934	1.178

Increasing the thickness of the varnish layer can be seen to progressively decrease the longitudinal stiffness while causing an increase in the transverse stiffness in the case here being dealt with. Similar calculations can be made for the other cases and with particulate added to determine the optimum thickness and particulate content for a given set of numbers.

TWO VARNISH LAYERS: ONE ON EACH SURFACE.

The more usual case to be considered is that of two layers of varnish one of which carries the filler and represents a ground coat. To simplify the mathematics, the layers will be taken as being one on each surface of the spruce. The expression now becomes:

$$(EI)_T = (EI)_s + (EI)_{v1} + (EI)_{v2}$$

Then $$E_T = E_s \; I_s/I_T + E_{v1} \; I_{v1}/I_T + E_{v2} \; I_{v2}/I_T$$

Using the values given above and assuming the same varnish is used for both layers and that E_{v2} carries the filler and we take E_T in terms of E_L. The expression for two varnish layers becomes:

$$E_T = h^2/(h + 2t)^3 \; [h \; E_s + 3t_1 \; E_{v1} + 3t_2 \; E_{v2}]$$

$$= 0.3141 \; (3 \; E_s + 0.09 \; E_{v1} + 0.09 \; E_{v2})$$

$$= 0.3141 \; (3 \; E_s + 0.027 \; E_s + 0.09 \; E_{v2})$$

E_T for a ground coat and a clear varnish layer for varying volume fractions of filler as a function of E_L are as follows:

V_F	E_{vF}/E_L	E_T/E_L
0.0	0.30	0.9593
0.1	0.57	0.9669
0.2	0.84	0.9745
0.4	1.38	0.9898
0.6	1.92	1.0051
0.8	2.46	1.0203
1.0	3.00	1.0356

With two layers in this example 50% filler is required to return the elastic modulus to the level of the unvarnished spruce. The effect on the cross grain modulus is shown below where it will be noted that 50% filler increases the cross grain elastic modulus by 50%.

V_F	E_{vF}/E_R	E_T/E_R
0.0	3.0	1.1119
0.1	5.7	1.1882
0.2	8.4	1.2646
0.4	13.8	1.4172
0.6	19.2	1.5699
0.8	24.6	1.7225
1.0	30.0	1.8752

TWO VARNISH LAYERS ON ONE SURFACE

When a clear varnish layer is placed over the ground coat, as would be the case in normal practice, the mathematical approach adopted above arrives at an unexpected result. The expression for the stiffness factor now becomes:

$$(EI)_T = (EI)_s + (EI)_{v1} + (EI)_{v2}$$

$$E_T = E_s\ h^3/(h+t_1+t_2)^3 + E_{v1}\ 3T_1h^2/(h+t_1+t_2)^3 + E_{v2}\ 3t_2(h+t_1)^2/(h+t_1+t_2)^3$$

This can be written:

$$E_T = h^3/(h+t_1+t_2)^3\ [E_s + 3t_1/h\ E_{v1} + 3t_2/h\ E_{v2}\ (1+ 2t_1/h+t_1^2/h^2)]$$

For $t << h$, and $t_1 = t_2$ this can be simplified a little:

$$E_T = h^3/(h+2t)^3\ [E_s + 3t/h\ \{E_{v1} + E_{v2}\ (1+2t/h)\}]$$

Substituting the numerical values above for $E_s = E_L$ and taking $E_{v1} = E_{v2} = 0.3E_L$ we get:

$$E_T = 0.9423\ [E_s + 0.03(E_{v1} + 1.02\ E_{v2})]$$

$$= 0.9423\ (1.01818\ E_s)$$

$$= 0.9594\ E_s\ (= E_L)$$

which compares with the value for the single varnish layer.

For the case where the first varnish layer contains the filler we can write for $E_{v1} = E_{vF} = V_FE_F + (1 - V_F)E_{v1}$ which for $E_s = E_L$ becomes $E_{vF} = [3V_F + 0.3(1 - V_F)]\ E_s$

and $E_T = 0.9423\ [1.00918\ E_s + 0.009\ E_{vF}]$ with the results tabulated as before:

V_P	E_{VP}/E_L	E_T/E_L
0.0	0.3	0.9535
0.1	0.57	0.9558
0.2	0.84	0.9581
0.4	1.38	0.9627
0.6	1.92	0.9672
0.8	2.46	0.9718
1.0	3.00	0.9764

The effect on the cross grain stiffness in terms of the effective elastic modulus, taking $E_S = E_R$ and using the same numbers:

$$E_T = 0.9423\ (1.02754\ E_S + 0.009\ E_{VP})$$

The results of the calculation are:

V_P	E_{VP}/E_R	E_T/E_R
0.0	3.0	0.9937
0.1	5.7	1.0166
0.2	8.4	1.0395
0.4	13.8	1.0853
0.6	19.2	1.1311
0.8	24.6	1.1769
1.0	30.0	1.2227

If this mathematical approach is correct, there is a difference between putting a ground coat under a second varnish layer and on the other side of the wood to the varnish layer. It does seem strange that the ground coat under the varnish should have such a little effect. Clearly more work is needed in this area.

DAMPING DUE TO VARNISH

The effect of varnish on damping is important and has been dealt with by both Schelleng and Ono and will not be discussed except to say that Ono who confined his study to spruce, found that varnishing had least effect in the L direction causing a slight decrease in E_L and about a 50% increase in damping. The effect of varnishing was more dramatic in the R direction; E_R was more than doubled while the damping was also doubled. He concluded that varnishing could be beneficial when the value of E_R was low in the range but detrimental when E_R was high in the range.

Schelleng arrived at more general conclusions related to violins. The loss in output on varnishing was serious enough for the amounts to be kept to a minimum by reducing the varnish on the top to 1/3 that on the back thus achieving equal losses in the top and the back with a total overall lowering of losses in output. Varnishing could seriously detune the plates and might require varnishing before tuning except for the final coat. He thought that using highly resonant wood reduced losses and made varnishing less critical. The results have been summed up in the adage "Not too hard, not too soft and not too much".

CONCLUSION

These calculations show that for a spruce plate with the typical properties chosen, the longitudinal stiffness is reduced by about 2% and the transverse stiffness increased by about 6% when a layer of natural resin varnish 0.03 mm thick is applied to one surface. Doubling the thickness of the varnish layer reduces the longitudinal stiffness by about 4% while increasing the transverse stiffness by about 11%.

A varnish layer on both surfaces has the same effect as doubling the thickness on one surface for the same total thickness.

When one varnish layer is loaded with a particulate e.g. ground glass, to increase the stiffness, about 30% is required to restore the longitudinal stiffness which amount would increase thetransverse stiffness by about 25%.

In the case with one varnish layer on each surface, 60% of the particulate used in this example is required to restore the longitudinal stiffness which amount would increase the transverse stiffness by about 60%.

For two layers on one surface, the longitudinal stiffness is not restored in this example, remaining down about 2% while the transverse stiffness is raised about 20%.

These predictions are generally in line with some practical trials [8] although the limited data supplied prevents a more detailed comparison.

ACKNOWLEDGEMENT

I wish to thank Neil Kilgour for stimulating discussion which led to this paper.

APPENDIX

The numerical values for the material parameters are as follows:

For $E_s = E_L$

$E_L = 10 \times 10^9$ Pa
$E_{v1} = E_{v2} = 0.3\ E_L$
$E_p = 3\ E_L$
$h = 3.00$ mm
$t_1 = t_2 = 0.03$ mm

For $E_s = E_R$

$E_R = 1 \times 10^9$ Pa
$E_{v1} = E_{v2} = 3\ E_R$
$E_p = 30\ E_R$
$h = 3.00$ mm
$t_1 = t_2 = 0.03$ mm

For the single varnish layer the expressions used for I_T, I_s and I_v are as follows:

$$I_T = [b(h + t)^3]/12; \quad I_s = [bh^3]/12; \quad \text{and} \quad I_v = [bth^2]/4$$

where b is the width and h is the thickness of the beam and t is the thickness of the varnish layer. It follows that:

$$I_s/I_T = h^3/(h + t)^3 \text{ and } I_v/I_T = th^2/(h + t)^3$$

For the case of two varnish layers, one on each surface, we have:

$I_s = bh^3/12$; $I_{v1} = bt_1h^2/4$; $I_{v2} = bt_2h^2/4$; $I_T = b(h + t_1 + t_2)^3/12$

and $I_s/I_T = h^3/(h + t_1 + t_2)^3$; $I_{v1}/I_T = 3t_1h^2/(h + t_1 + t_2)^3$;

and $I_{v2}/I_T = 3t_2h^2/(h + t_1 + t_2)^3$. Substituting these in

$$(EI)_T = (EI)_s + (EI)_{v1} + (EI)_{v2}$$

$$E_T = E_s\ I_s/I_T + E_{v1}\ I_{v1}/I_T + E_{v2}\ I_{v2}/I_T$$

we have $E_T = h^2/(h + 2t)^3[h\ E_s + 3t_1\ E_{v1} + 3t_2\ E_{v2}]$

where $t_1 = t_2$.

For two varnish layers on one surface (one of which will be a ground coat carrying a filler) we have the following:

$$E_T = E_s\ I_s/I_T + E_{v1}\ I_{v1}/I_T + E_{v2}\ I_{v2}/I_T$$

where $I_T = b(h+t_1+t_2)^3/12$; $I_s = bh^3/12$; $I_{v1} = bt_1h^2/4$ and

$$I_{v2} = bt_2(h+t_1)^2/4$$

and $I_s/I_T = h^3/(h+t_1+t_2)^3$; $I_{v1}/I_T = 3t_1h^2/(h+t_1+t_2)^3$ and

$$I_{v2}/I_T = 3t_2(h+t_1)^2/(h+t_1+t_2)^3 \quad \text{giving}$$

$$E_T = h^3/(h+t_1+t_2)^3\ [E_s + E_{v1}\ 3t_1/h + E_{v2}\ 3t_2/h(1+2t_1/h+t_1^2/h^2)]$$

REFERENCES

1 Dipper A.,"The use of mineral ground coatings for violin varnish", VSA Journal, Vol XIII (2), 1993, p43.

2 Barlow C.Y. and Woodhouse J., "Firm ground", The STRAD, Vol 100, 1989, Mar p195 and Apr p275.

3 Haines D.W. and Chang N., "Application of graphite composites in musical instruments", CAS NL #23, 1975, p13.

4 Tingry P.F., "The painter and varnisher's guide", G. Kearsley, London, 1804, p124.

5 Schelleng J.C., "Acoustical effects of violin varnish", J. Acoust.Soc.Amer. Vol 44 (5) 1968, p1175-1183.

6 Ono T., "Effects of varnishing on acoustical characteristics of wood used for musical instrument soundboards", J. Acoust.Soc.Japan. (E) Vol 14 (6) 1993, p397-407.

7 Scanlan R.H., "Factors affecting plate vibrations", CAS NL #5, May 1966, p7.

8 Hutchins M.A., "Effects on spruce test strips of four-year application on four different sealers plus oil varnish", CAS Journal Vol 1 (7) May 1991, p11-16.

ADDENDUM

THE EFFECT OF A SILICA LAYER

It is of some interest to explore in this context the effect of a silicate layer. It has been suspected for some time that Potassium Silicate (or the more hygroscopic Sodium Silicate) was painted onto the surface of violins, or even a more neutral Calcium Silicate (the others being highly alkaline with disastrous results for the wood). The aim no doubt was to stiffen the violin after it had been made as light as possible. It may have had tuning significance raising certain characteristic frequencies e.g. AO.

The elastic modulus of SiO_2 (Quartz) is typically about 70 x 10^9 Pa so the equation for one varnish layer, viz.

$$E_{TP} = h^3/(h + t)^3 \; [E_B + E_{VP}(3t/h)]$$ was used.

t(mm)	$h^3/(h + t)^3$	3t/h	$E_T(=E_L)$	$E_T(=E_R)$
0	1.0000	0	1.0000	1.0000
0.01	0.9900	0.01	1.0593	1.6830
0.02	0.9803	0.02	1.1175	2.3527
0.03	0.9706	0.03	1.1744	3.0089
0.04	0.9610	0.04	1.2301	3.6518
0.06	0.9423	0.06	1.3381	4.9000
0.08	0.9241	0.08	1.4416	6.0991
0.10	0.9063	0.10	1.5047	7.2504

One can see that a substantial effect is to be expected. Both moduli are increased; a 10 um thick layer increases E_L by about 6% and E_R by about 70% on this model.

Elastic modulus was used in this paper as this gave a comparison with published results of experiments. This simplified treatment tends to give higher values for the larger thicknesses of varnish as pointed out by Professor Jim Woodhouse (private communication) since the shift in neutral axis cannot then be ignored.