Proposed standard glue strength testing method for luthiers

For a long time, I have been looking for glue strength data that will be of use to small volume guitar builders such as myself. So far, I have found very little useful data. Most of the available data are related to industrial uses such as plywood and beam lamination.

Luthiers choose different glues for a variety of reasons: Cost, availability, heat resistance, reversibility, gap-filling, color, ease of use, working time, etc. I often hear partisans of some kind of glue state that it is the strongest/best/most heat resistant. This article addresses glue strength at nominal conditions (room temperature, dry) and proposes a standard test method. Having good basic strength data should help luthiers choose the glue they use.[1] If different people use the same test method, then the results can be more easily and more confidently compared.[2]

I have access to a calibrated INSTRON testing machine[3]: The ideal tool for testing the strength of small specimens. The INSTRON tester provides precision control over loading rate and highly accurate and repeatable results (within +/- 1%). The results presented here were performed on a calibrated INSTRON tester. However, any accurate load measuring tool could be used for this testing.

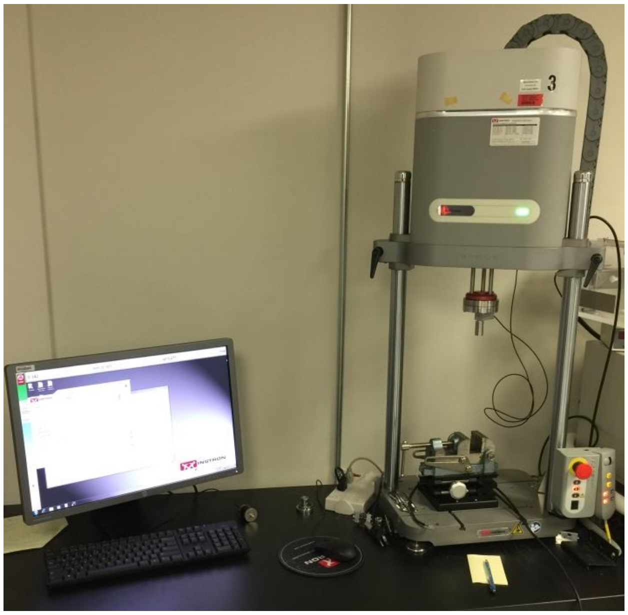


Figure 1: INSTRON Tester

[1] As I noted in AL #100, stresses on guitars from normal loading (strings and playing) are low compared to the strength of wood and glue.

[2] This method may also allow you to have confidence in glue that, for instance, is beyond its sell-by date, has been frozen, etc., by comparing its performance to a control set of data.

[3] Calibration is a process of continual testing and maintenance that ensures that an instrument gives true results and continues to do so at all times.

Good glue joints

Many factors may contribute to the strength of the glue joint Most luthiers attempt to make joints that are tightly fitted, with smooth and clean surfaces that are well-clamped and are allowed to cure fully before unclamping.

Primary factors affecting glue joint strength:

a. Good glue (glue that is not too old and has been stored properly, proper mixing of epoxy, etc.)
b. The materials being joined
c. Tight joint (no gaps)
d. Good clamping during cure
e. Cleanliness (no foreign matter in the glue or on the surfaces being glued)
f. Correct temperature and humidity for curing
g. Clamping maintained until the glue is fully set or cured

It's easy to make a bad glue joint. We want to know how good a glue can be in a properly executed joint. This test follows all the good practices noted above.

This article assesses the effect of wood species on glue joint strength: This set of data has samples made from Sitka spruce, bubinga, and Honduran mahogany. The test samples are loaded in the longitudinal direction (parallel to the grain). To use the radial or tangential direction of the wood would likely result in many failures within the wood, not the glue, because wood strength in these directions is much weaker than in the longitudinal direction. All you would learn is that the glue was stronger than the wood, for that sample.

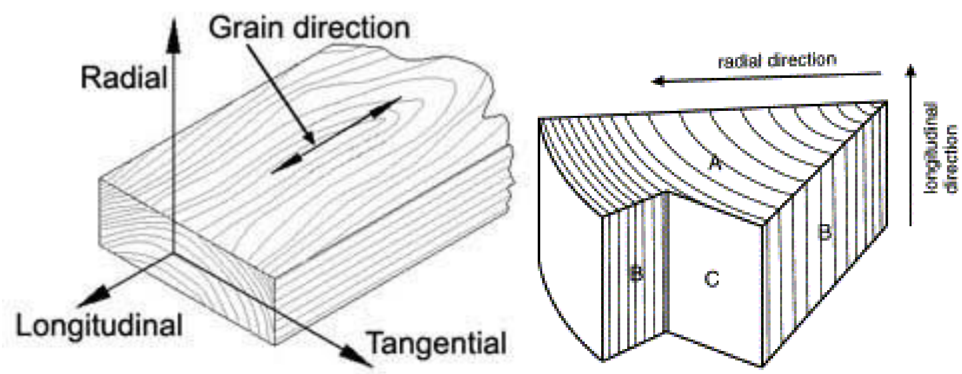


Figure 2: Direction Definition for Wood Structure

Test Samples and Coupon Design

I have been strength testing materials and assemblies for 30 years as part of my day job as a design engineer and structural strength analyst. I have applied that learning to the design of these tests. To get good results from a test, the test article must be properly designed.

I am proposing a relatively small coupon to save time and cost when preparing a large number of specimens. Since the materials used (wood and a thin glue bond line) are quite rigid for the purposes of this test, there will be no significant necking, and the parts are homogenous through their thickness, the coupon size will not significantly affect the results.

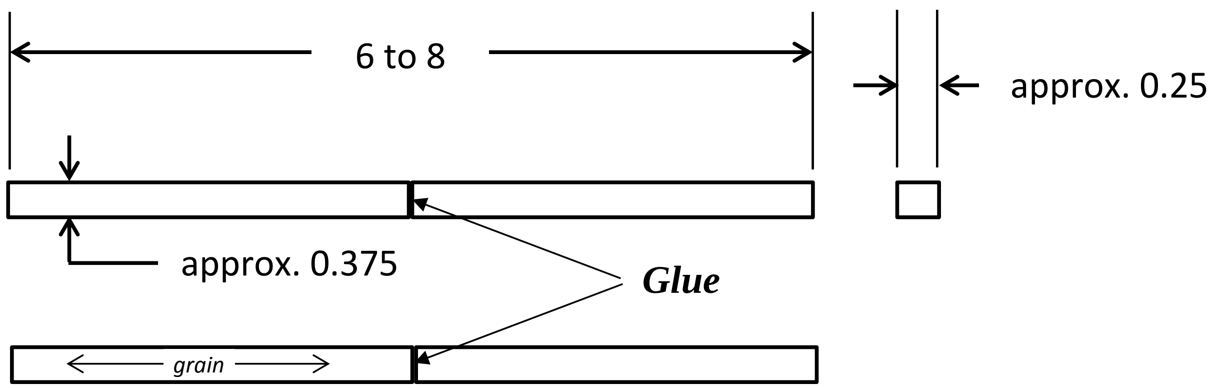


Figure 3: Tension Test Coupon Design (dimensions in inches)

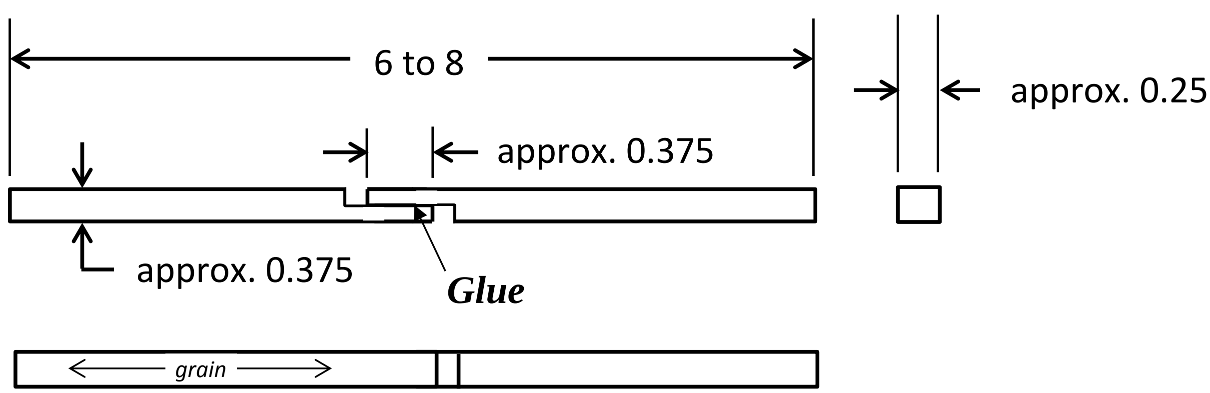


Figure 4: Shear Test Coupon Design (dimensions in inches)

Figure 3 and Figure 4 show the design of the tension and shear test coupons (dimensions are in inches[4]). The grain is oriented with the length of the specimens. The exact dimensions are not critical since you will be measuring the glue area of each sample. This will give an accurate measure of stress.

In addition, multiple samples are needed to provide reliable results. To get reasonably reliable results for a failure test like this (variables data), you need at least 15 samples, and more samples, up to about 50 or 100, is always better (though 15 is OK). This is because all things vary. In order to understand that variation and how it affects what you are measuring (glue strength), you need to try and "capture" that variation by using multiple samples.[5] It is a common misconception that a single test or a few tests can accurately characterize a material or condition.

Making the test coupons

1. Cut billets to make long plate (or panel) of L-direction coupons. Figure 5. I start with material about 1 inch thick and about 8 inches long (in the grain direction). You can split this to double the number of coupons by resawing this thick plate on a precision bandsaw.
2. Joint edges and glue the blocks into one long plate with grain running crosswise. Figure 6.
3. Thickness sand the plate to approximately 0.375 inch thick; and cut plate in half lengthwise (at a 90° angle to the grain).
4. Joint the edges of the two plate pieces for tension coupons or rabbet their edges (I use a table saw with a precision blade) for shear coupons (keep shear surface at the center of the coupon)
5. Glue up the two parts of the specimen plate. I use brads for alignment pins for the shear coupons to keep the two edges of the glued joint parallel. Figure 7 and Figure 8.
6. Clean up squeeze-out (this is especially important for the shear coupons; I use a glue-clearing chisel for this). (I thickness sand the tension coupon plate to provide identical glue surfaces and to remove all squeeze-out.)
7. Slice the coupon plates into approximately 0.25 inch thick coupons using a table saw or precision bandsaw and a rigid fence.
8. Measure coupon glue area dimensions (width and thickness of tension coupons; thickness and shear lap length for the shear coupons). Compute glue area (thickness times width for tension coupons; thickness times shear lap length for shear coupons).
9. Mark both ends of each coupon with its code. Because you are measuring each coupon's glue area, you need to be able to link each test load with each individual coupon, in order to accurately compute the failure stress (strength).

[4] Corresponding metric dimensions are: 150-200mm in length, 6-10mm in width and thickness and approximately 10mm for the shear overlap.
[5] I am intentionally not using statistically precise language here because I don't what to put off readers who haven't studied statistics. Please see the further reading section for references to statistical methods.

Figure 5: Blocks Ready to be Made into the Coupon Plates

Figure 6: Gluing the Coupon Plates (After Jointing the Edges of the Blocks)

Figure 7: Glued up Plate of Tension Coupons, Ready to Slice into Coupons

Figure 8: Glued up Plate of Shear Coupons, Ready to Slice into Coupons

Figure 9: Detail of Shear Coupon Plate Glue Joint

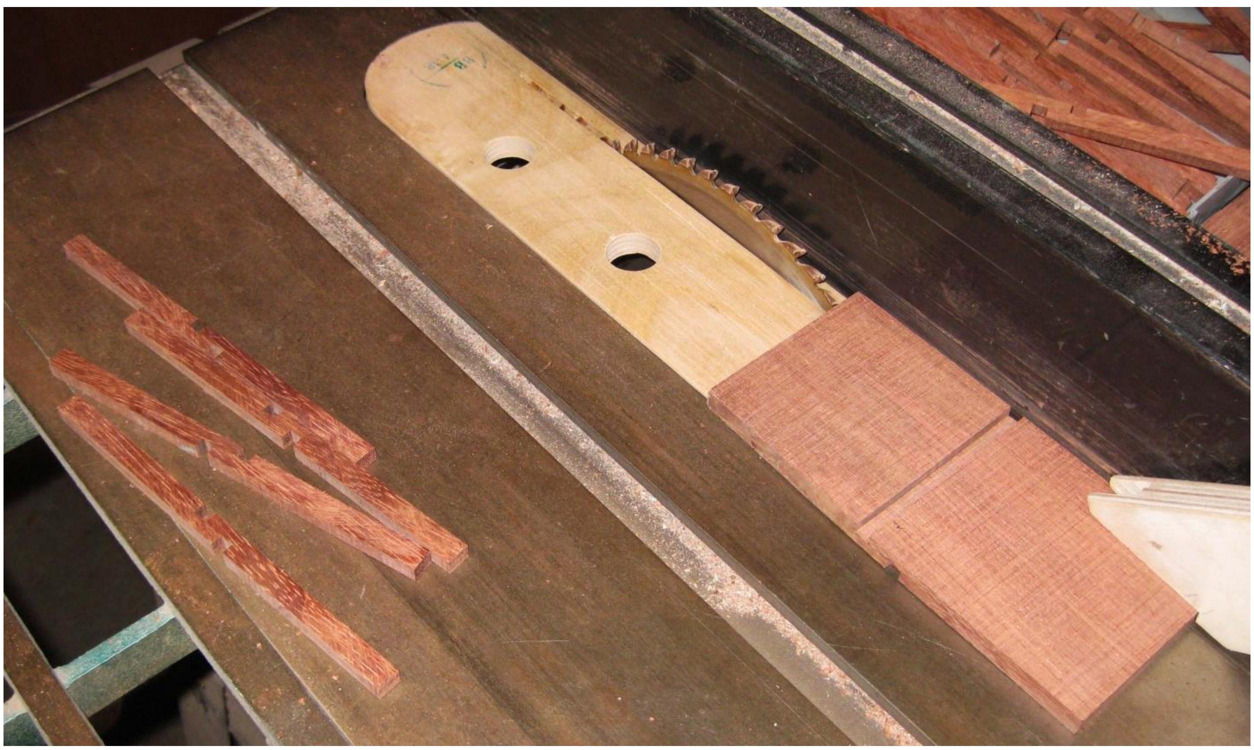


Figure 10: Slicing Coupons from the Shear Test Coupon Plate

Figure 11: Completed Coupons: Tension (top) and Shear (bottom)

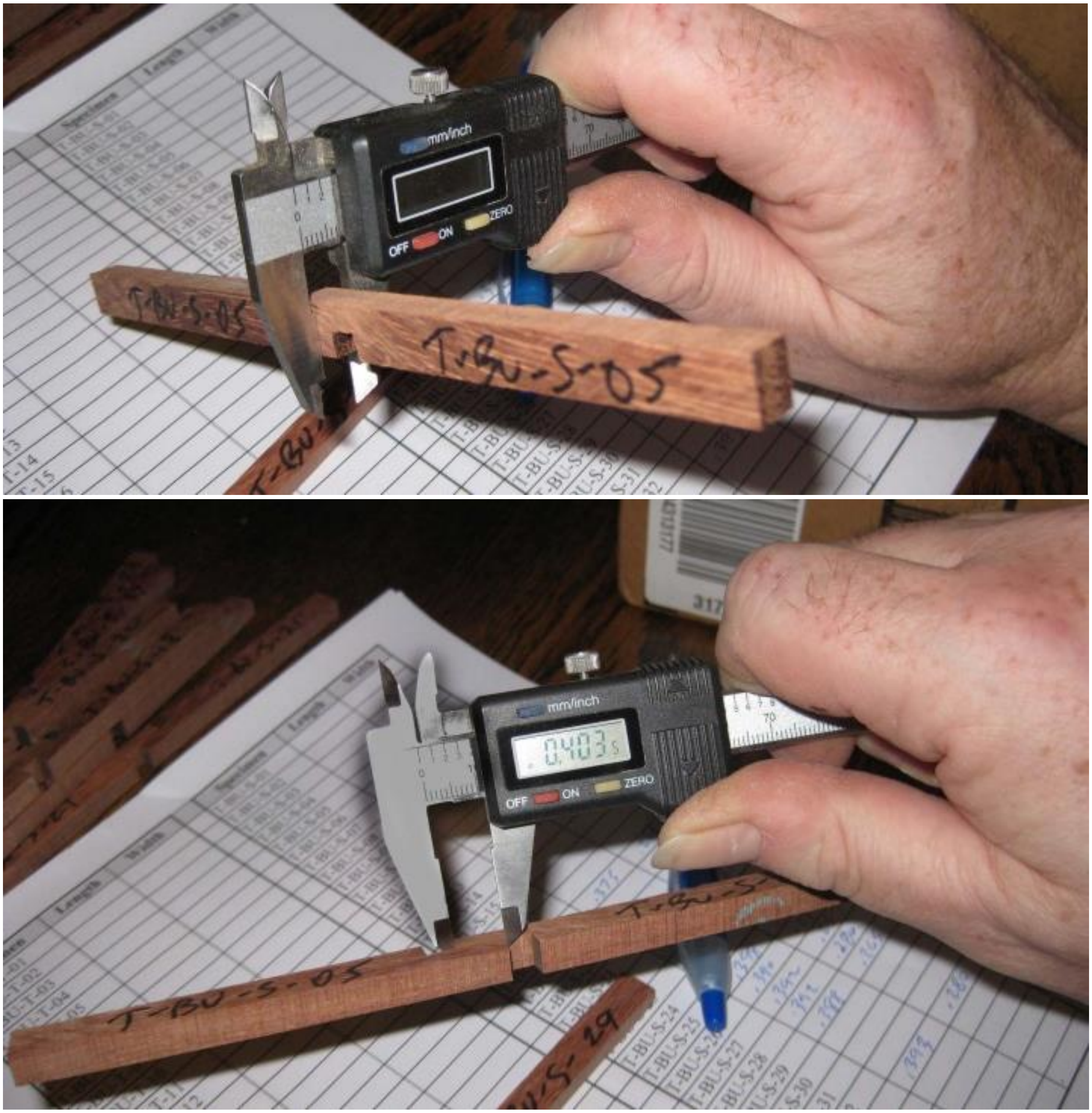
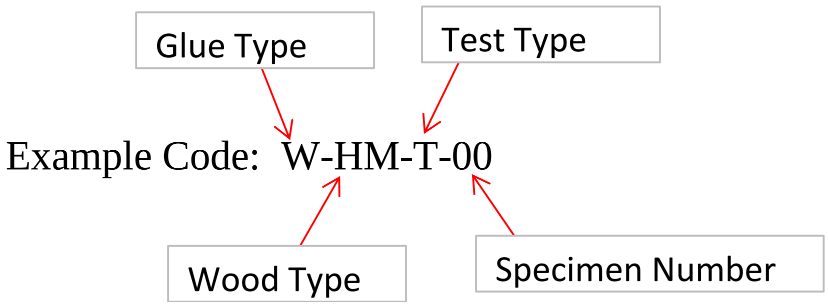


Figure 12: Measuring the Glue Area of a Shear Test Coupon

This is the test coupon coding I am using. It’s pretty convenient and I recommend it. Coding the samples makes it easy to ensure you record the correct data and makes failure analysis easier (for any weird failures).



(Glue type - W=white, T=Titebond, P=polyurethane, H=hide, E=epoxy, C=superglue)
(Wood type – HM=Honduran mahogany, IR=Indian rosewood, SS=Sitka spruce, BU=bubinga)
(Test type: T=tension, S=shear)

Test method

1. Place the samples in a properly set-up tension testing machine and pull them to failure
2. Record the peak load
3. Compute stress for each sample by dividing the peak load by the computed glue area[6]

I recommend a loading rate of 0.3 mm per minute for these tests, because the specimens are very stiff. I also recommend reporting the results in both US units (psi or ksi) and metric units (KPa or MPa).

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[6] Strength is always reported in units of stress, for instance pounds force per square inch (psi) or Pascals (Pa = Newtons per square meter; often with a kilo- (KPa) or mega- (MPa) prefix) Why stress and not load? Because the size of the object obviously makes a big difference in the load it will carry. Dividing the failure load by the (appropriate) area normalizes the data for the material (rather than the specimen). A 1 inch by 1 inch part will carry more load than a 0.1 inch by 0.1 inch part made from the identical material.

Results

Below are presented the first set of test data I gathered and statistical analysis of those data.

Tests performed:

Table 1: Summary of Sample Size for All Tests

Wood	Code	Shear Test	Tension Test
Bubinga and Titebond	T-BU-S/-T	15 samples	18 samples
Sitka Spruce and Titebond	T-SS-S/-T	19 samples	15 samples
Honduran Mahogany and Titebond	T-HM-T	-------	16 samples
Honduran Mahogany and Hide Glue	H-HM-T	-------	21 samples
Honduran Mahogany and CA Glue	CA-HM-T	-------	16 samples
Honduran Mahogany and Hide Glue + Hide Glue[7]	HH-HM-T	-------	14 samples
Honduran Mahogany and Hide Glue + Shellac[8]	HS-HM-T	-------	14 samples
Total Samples		**34**	**114**

For the tests, fresh glue was used. The hide glue was from Rockler, freshly made to the recipe on the label (starting with dry "pearls" of hide glue). The CA (cyanoacrylate or "super") glue was Stewart MacDonald's glue, their "20" grade medium thickness glue (no accelerator was used). The shellac and prior hide glue treatments were tested at the request of a fellow GAL member.

Overall results are shown in Table 2 and Table 3. Note that most of the shear samples failed in the wood (glue was stronger than the wood). The elapsed time for each test was about 10 seconds from start to failure. The loading rate (displacement control) was 0.3mm per second (quite slow, nothing like a sharp blow; but also nothing like long-term creep.)

[7] Gluing surfaces of the pieces were treated with ½-strength hide glue 24 hours prior to bonding
[8] Gluing surfaces of the pieces were treated with 1-pound cut shellac 24 hours prior to bonding

Table 2: Basic Statistics for the Tests Performed (US Units)

Code	N	Max (psi)	Min (psi)	Range (psi)	Mean (psi)	Median (psi)	Std. Dev. (psi)	Percent of samples showing glue failure
T-BU-T	18	2258	766	1491	1526	1446	402	100%
T-BU-S	15	2212	640	1573	1412	1385	415	4 of 15 , 27%
T-SS-T	15	1900	685	1215	1118	1064	289	100%
T-SS-S	19	2258	645	1613	1161	1050	435	7 of 19, 37%
HH-HM-T	14	2718	327	2391	1356	1274	816	100%
HS-HM-T	14	1395	133	1262	681	635	432	100%
CA-HM-T	16	2948	895	2053	2237	2489	578	100%
T-HM-T	16	1938	744	1194	1398	1408	330	100%
H-HM-T	21	2777	1122	1654	1895	1901	397	100%

Table 3: Basic Statistics for the Tests Performed (Metric Units)

Code	N	Max (MPa)	Min (MPa)	Range (MPa)	Mean (MPa)	Median (MPa)	Std. Dev. (MPa)	Percent of samples showing glue failure
T-BU-T	18	15.57	5.28	10.28	10.52	9.97	2.77	100%
T-BU-S	15	15.25	4.41	10.84	9.74	9.55	2.86	4 of 15 , 27%
T-SS-T	15	13.10	4.73	8.38	7.71	7.33	1.99	100%
T-SS-S	19	15.57	4.44	11.12	8.01	7.24	3.00	7 of 19, 37%
HH-HM-T	14	18.74	2.25	16.49	9.35	8.78	5.62	100%
HS-HM-T	14	9.62	0.92	8.70	4.69	4.38	2.98	100%
CA-HM-T	16	20.32	6.17	14.15	15.42	17.16	3.99	100%
T-HM-T	16	13.36	5.13	8.23	9.64	9.71	2.28	100%
H-HM-T	21	19.15	7.74	11.41	13.07	13.11	2.74	100%

Figure 13 shows some test specimens before and after failure testing. Tension test in the left two photos and shear test in the right two photos.

Figure 13: Specimens Under Test

Figure 14 shows a failed shear test specimen made of Sitka spruce, showing the failure in the wood itself (the majority of the shear specimens failed in the wood, not the glue.)

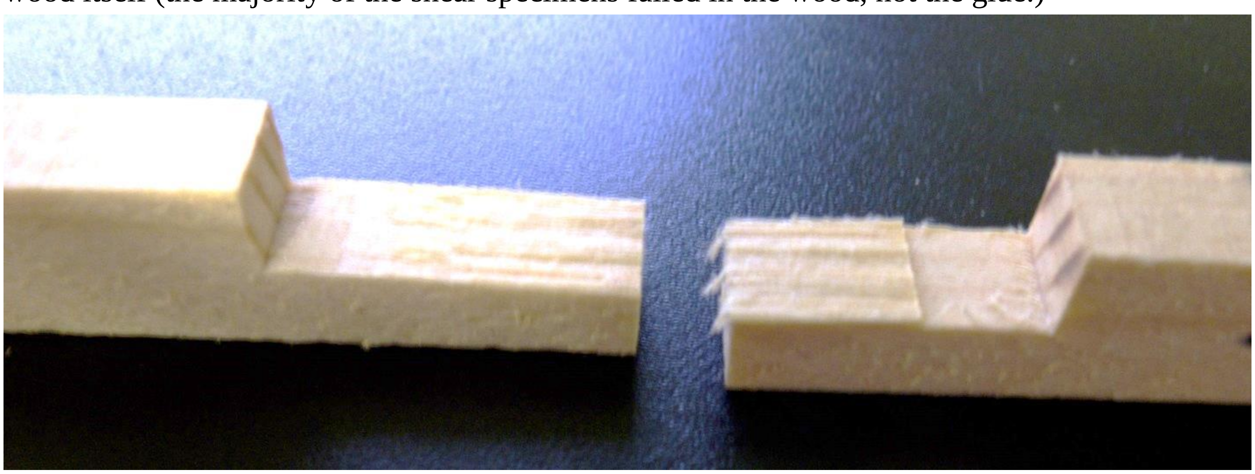

Figure 14: Shear Test Failure Faces (Failure in Wood)

Figure 15: Pile of Failed Specimens Following Testing

Figure 16 shows a typical load-displacement curve (these tests showed similar results throughout). This shows the overall behavior of the test specimens. What you see is a nearly-linear increase of load with displacement, then a brittle failure (no stretching before failure). Note that for an approximately 150mm long sample, it only displaced 4.5mm (approximately 3%) which is very little elongation; this is also typical of brittle failures. Note that the load achieved was approx. 960 N (215 lbf) for a sample that is approximately 0.25 inch X 0.375 inch, 0.094 in^2 (less than 1 cm^2). (The glue is very strong.)

In contrast to the brittle failure exhibited by these test specimens and shown graphically in Figure 16, Figure 17 shows a typical stress-strain curve (comparable to the load-displacement curve shown in Figure 16), which shows the stretching (plastic deformation) of the material prior to failure (noted as strain hardening and necking in the figure).

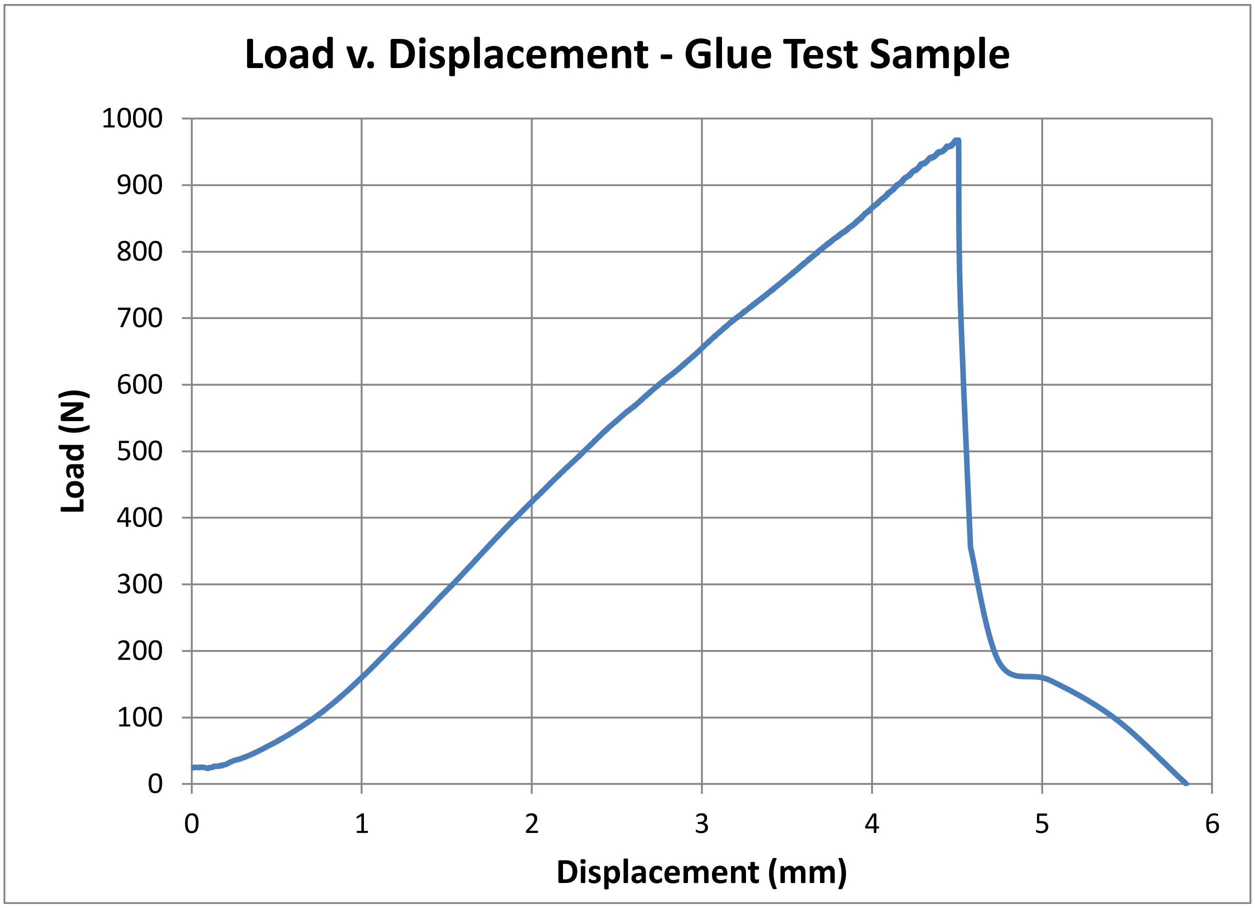

Figure 16: Typical Load-Displacement Curve for All Specimens

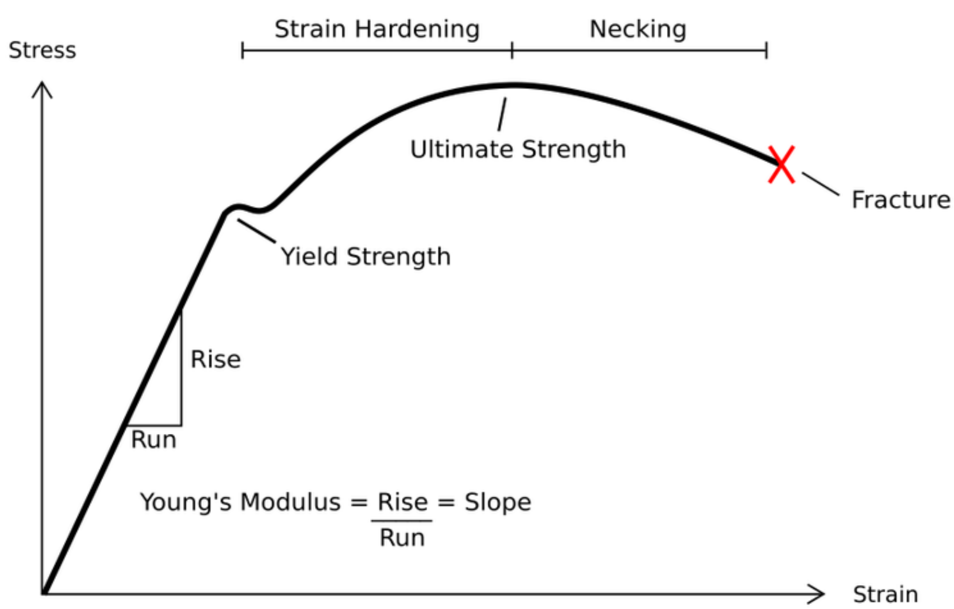

Figure 17: Typical Stress-Strain Curve for a Ductile Material

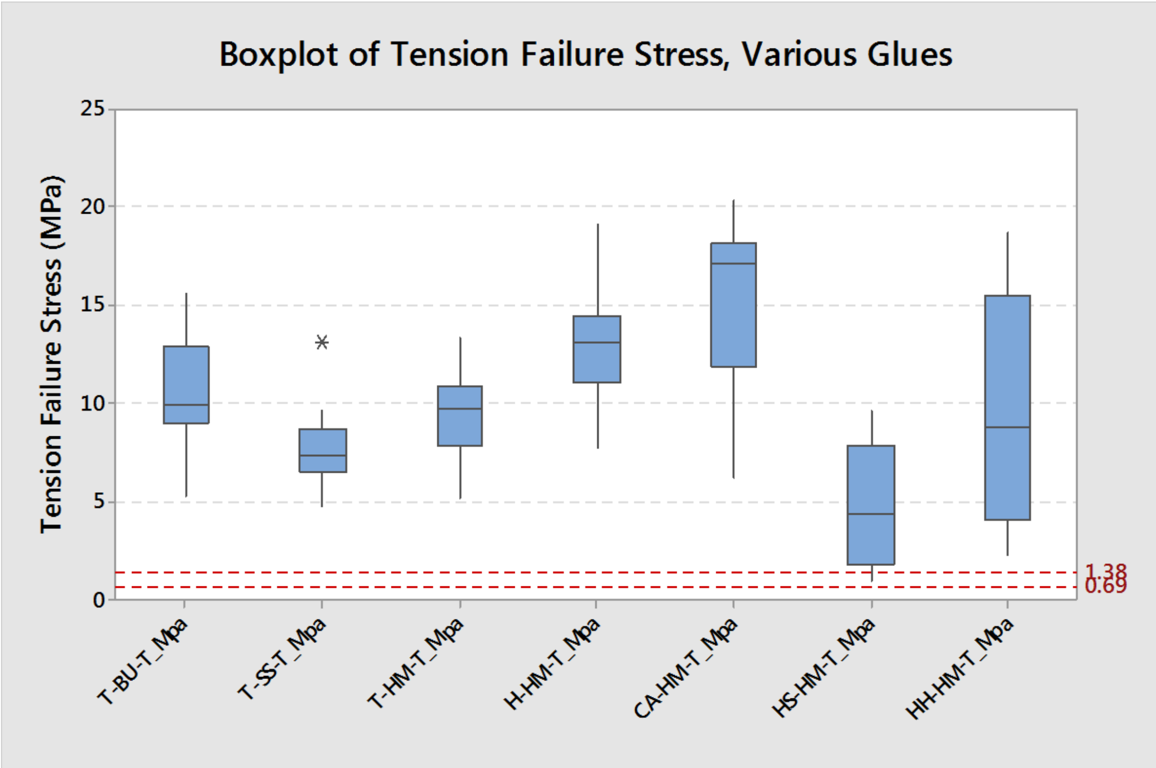

Figure 18: All Tension Test Data - Compared

Figure 18 shows all of the tension test data, compared in a box plot.[9] What you will notice is that the CA glue is strongest, followed by hide glue and then Titebond, with the hardwoods (bubinga and Honduran mahogany) showing stronger bonds that the Sitka spruce for the Titebond. Both the surface treatments prior to hide gluing showed lower strength and more scatter. The reference lines at the bottom show the highest stress I computed for glue under normal loading on a steel string guitar and a higher line with a 2X safety factor applied to the highest computed stress. Note that all the glues are strong enough to react to applied loading (the data shown by the box plots are much higher than the reference lines).

If a box plot is shorter (top to bottom) and more symmetrical, that indicates a more consistent process or material. Plain hide glue and Titebond have similarly shaped boxplots, while the other glues (and treatments) show more scatter. The CA glue has the highest strength individual sample and the highest average strength; but it also shows a lot of scatter and a long “tail” on the low end. This may indicate that it is more sensitive to gluing technique than the other adhesives. (It may be easier to end up with some weak bonds.)

[9] A box plot shows the distribution of the data. The middle line is the mean (average), the box is the middle 50% of the data, and the whiskers show the highest and lowest 25% of the data.

As shown in Table 4, the comparisons of tension strength for all the types compared are statistically different for all glue types compared except for CA glue versus hide glue (p-value = 0.054) and Titebond on bubinga versus Honduran mahogany (p-value = 0.315)[10].

Table 4: 2-Sample T-Test Results Comparing the Various Glues in Tension Testing

	Titebond-Honduran	CA glue-Honduran	Hide glue-Honduran	Shellac treatment	Thin Hide Treatment	Titebond-Sitka	Titebond-bubinga
Titebond-Honduran	N/A	***0.000***	***0.000***	***0.000***	0.861	***0.018***	0.315
CA glue-Honduran	N/A	N/A	0.054	***0.000***	***0.003***	***0.000***	***0.000***
Hide glue-Honduran	N/A	N/A	N/A	***0.000***	***0.035***	***0.000***	***0.007***
Shellac treatment	N/A	N/A	N/A	N/A	***0.013***	***0.004***	***0.000***
Thin Hide Treatment	N/A	N/A	N/A	N/A	N/A	0.317	0.484
Titebond-Sitka	N/A	N/A	N/A	N/A	N/A	N/A	***0.002***
Titebond-bubinga	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Figure 19: Shear Strength of Titebond – Two Wood Species

[10] For all other p-values > 0.05, the likely cause is the very large scatter of the surface treated hide glue tests (HH- and HS-, thin hide and shellac). This causes the large scatter to overlap the other distribution.

Figure 19 shows the shear test results. Both plots are Titebond, one is for bubinga specimens and the other for Sitka spruce specimens. There is a slight difference between them; but remember that for these tests, the majority of the specimens failed in the wood. So the results mostly indicate the strength of the wood. Statistically, these two sets of data are not different – they are indistinguishable populations (p-value for 2-sample T-test is: 0.097).

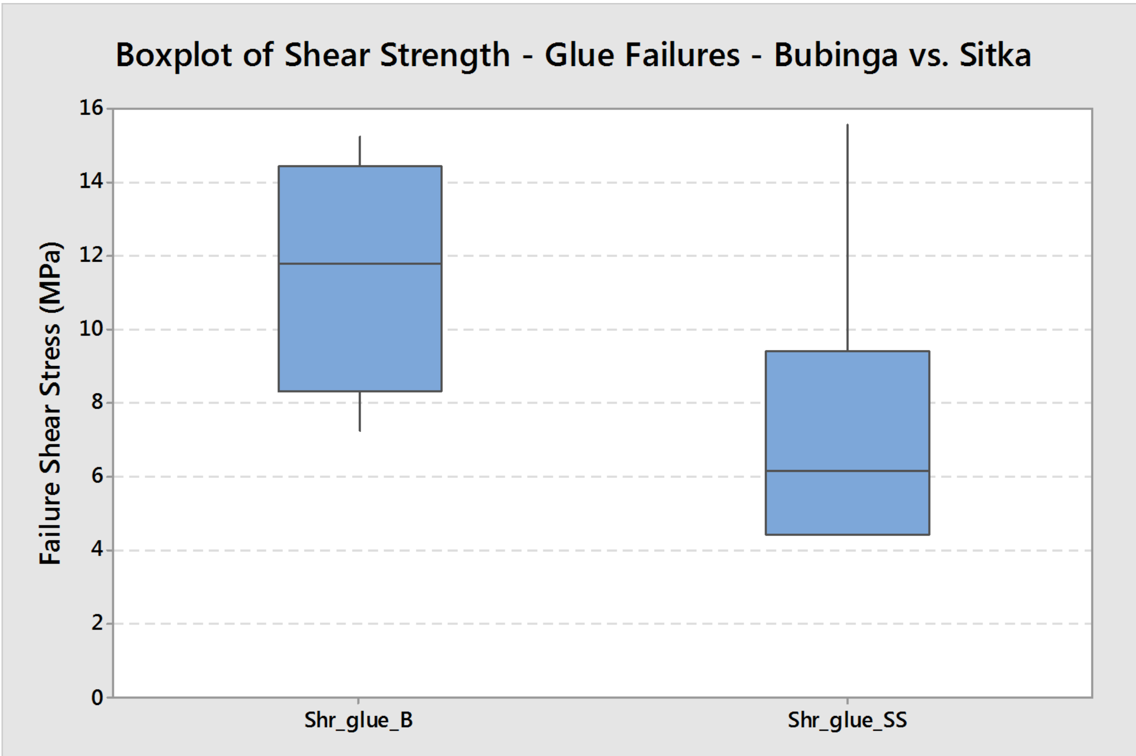

Figure 20: Shear Strength – Glue Failures Only

Figure 20 shows the same data as shown in Figure 19; but with only the glue failures included. These show that the shear strength of Titebond on bubinga appears to be higher than on Sitka spruce. However, there is no statistical difference between the two sets of data (p-value for 2-Sample T-Test is 0.146). This may be because the sample sizes are too small for the test to discern the difference, or there may actually be no significant difference in strength. *More testing is needed to determine which is the actual case.*

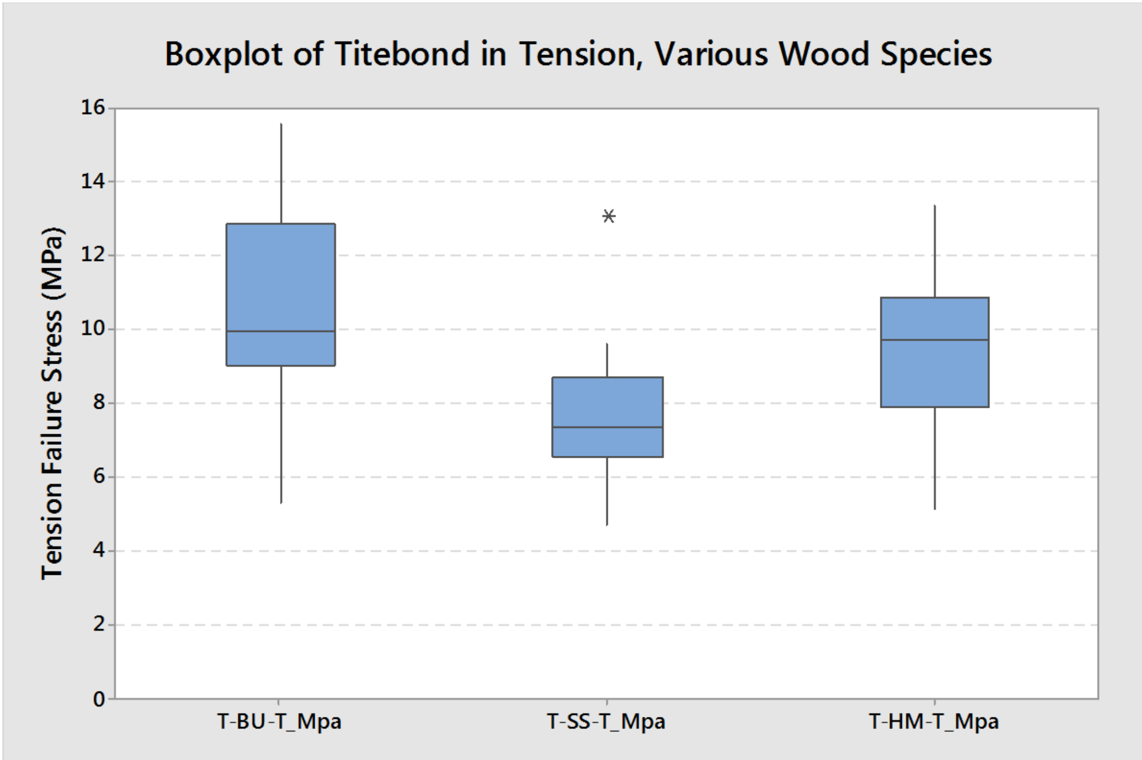

Figure 21: Tension Strength of Titebond for Various Wood Species

Figure 21 shows the tension strength of Titebond for three wood species: Bubinga, Sitka spruce, and Honduran mahogany. Note that the strength plots align with the strength of the wood (bubinga strongest, the Honduran mahogany, then Sitka spruce). Statistically, the Sitka spruce is different from the bubinga and the Honduran mahogany (p-values for 2-sample T-test are: 0.002 and 0.018, respectively). The bubinga and Honduran mahogany are not statistically distinguishable (p-value for 2-sample T-test is: 0.315)

Conclusion: What does all this mean?

My conclusions from this first set of tests are:

1. There are differences in tension strength between the various glues commonly used in guitar making: Hide glue, Titebond, CA glue.
2. However, all glues tested are significantly stronger in tension than the applied stresses under normal conditions in guitar making. (As I noted in my article in *American Lutherie* #100, guitars fail due to accident or weather, not due to normal loading.)
3. In shear, the glues tested will be stronger than the woods typically used in guitar making. Additional data would help solidify this conclusion.
4. The two surface treatments applied to the glue joints prior to gluing with hide glue (thin hide glue, shellac) both reduced the strength of the hide glue joint and increased the scatter of the data.

I intend to perform further glue tests and report the results in future editions of *American Lutherie*. In particular, I will be testing samples with the glue surfaces in the tangential and radial grain directions in the near future.[11] Based on the shear test data in the current set of tests, I am confident that the failures will be in the wood, not the glue.

[11] I have heard claims that glue is stronger when bonding on radial or tangential grained wood surfaces, as compared to gluing to end grain (longitudinal grain direction).

Appendix: Glue Stiffness and Hardness

Glue stiffness

I have often heard the claim than one glue or another is stiffer and is therefore better for instrument building.

Clearly, for the application of stringed instrument building, a strong and stiff glue is important. If the glue were mushy, then the instrument would fall (or ooze) apart. And it must be strong enough to carry the loads required of it (150 pounds or more of string tension in a steel string guitar).

However, beyond that, I am highly skeptical that there is any effect from glue stiffness or hardness[12] on the sound produced in a wooden instrument that properly constructed (that is, with tightly fitted, well clamped & glued joints.)

This is because there is almost no glue present in a well-made glue joint. And the effect of a structural element is directly proportional to its size. If there is almost no glue present, then it can have almost no effect.

To illustrate this, think of a spring. Imagine a 10-foot (3-meter) long spring. You apply a 100-pound force (445 N) to it and it stretches to 11 feet long. Now, take a 1-inch long segment of that same spring and apply the same 100-pound force. Will it stretch out an additional foot (like the 10-foot segment did)? It will not. It will stretch an amount that is proportional to its length, in this case: 1 inch / 120 inches X 12 inches = 0.00833 X 12 inches = 0.1 inch. It stretches from 1 inch to 1.1 inches (+10%) just like the long segment did (120 inches to 132 inches = +10%).

You would really notice that 12 inch stretch in the first example; but you likely wouldn't notice the 0.1 inch stretch in the second.

Extra length in the 10-foot spring example is exactly analogous to extra glue thickness in a glued joint (with a large gap filled with glue).

Hardness testing

I have sometimes heard it said that hardness testing of glue samples shows that hide glue (usually) is the hardest (and therefore the best) glue. There are major problems with such an assertion.

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[12] For any glue type that is typically used for guitar making: For instance Titebond, white glue, hide glue, "super" glue (cyanoacrylate), high quality epoxy, and polyurethane (Gorilla Glue)

The primary one is that the tests that people refer to in this case do not reflect the actual usage of the glue in the case we are interested in: Instrument building. People try to make testing samples out of blobs of glue. Blobs of glue bear no relationship to how glue is used: In very thin layers between two parts.

If you tried to test the actual use case, there's nothing to test. Even if you could get at the layer of glue, it would be like trying to hardness test plastic wrap.

Hardness testing is not informative because:

1. Informative data must accurately reflect the case under consideration. Blobs of glue do not meet this requirement. It is very difficult to make hardness coupons (that could be tested using, for instance, Shore hardness testing) from the glues commonly used for wood instrument building.
2. Hardness testing is sometimes used as an analogue for stiffness (or strength). The relationship can only be drawn when there exists a large body of data for the relationship. The relationship between hardness test results and strength or stiffness has not been established for wood glues and the use case of instrument building.

Areas for Further Testing

Other factors that would be useful to test and further areas for study:

More wood species
More glue types
Multiple glue lots (hard to do with off-the-shelf materials; but you could buy some from various stores significant distances apart)
Glue at various ages when used (old glue vs. new glue)
Aging the glued joints (test subsets of the samples at different times after their manufacture)
Various coupon sizes
Different dilutions of glues such as hide glue
Different curing conditions (temperature and humidity)
Different strength test conditions (temperature and humidity)
Cleaning methods for the gluing surfaces (for example with an acetone wipe – this would be important for testing glue on rosewood species)

Testing References:

The tensile method is equivalent to ASTM D 897, *Standard Test Method for Tensile Properties of Adhesive Bonds.* The specimen design is different; but the proposed coupon is equivalent and the ASTM D 897 coupon is impractical for small wooden samples.

The shear method is roughly equivalent to ASTM D 905, *Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading.* The proposed coupon will be less in pure shear than the ASTM D 095 coupon; but is still appropriate for the purposes of this test (a slightly mixed shear/tension failure is acceptable for comparative purposes).

Other ASTM shear tests for adhesive include: ASTM D 3163, *Standard Test Method for Determining Strength of Adhesively Bonded Rigid Plastic Lap-Shear Joints in Shear by Tension Loading*; ASTM D 3165 *Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies*. These other test coupons (refer to Figure 23, Figure 24, and Figure 25) are quite similar to the proposed coupon. These methods support the suitability of the proposed shear testing method.

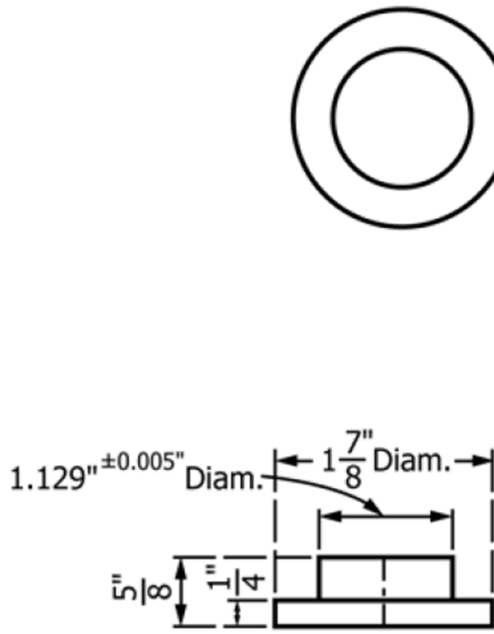

Figure 22: ASTM D 897 Tensile Test Coupon (One-half of a Set)

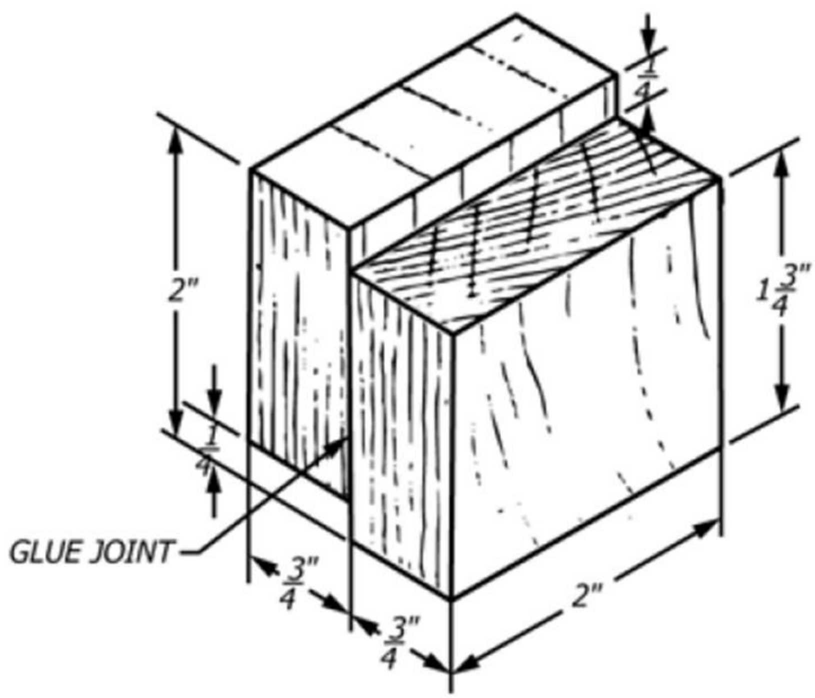

Figure 23: ASTM D 0905 Shear Test Coupons (Wood)

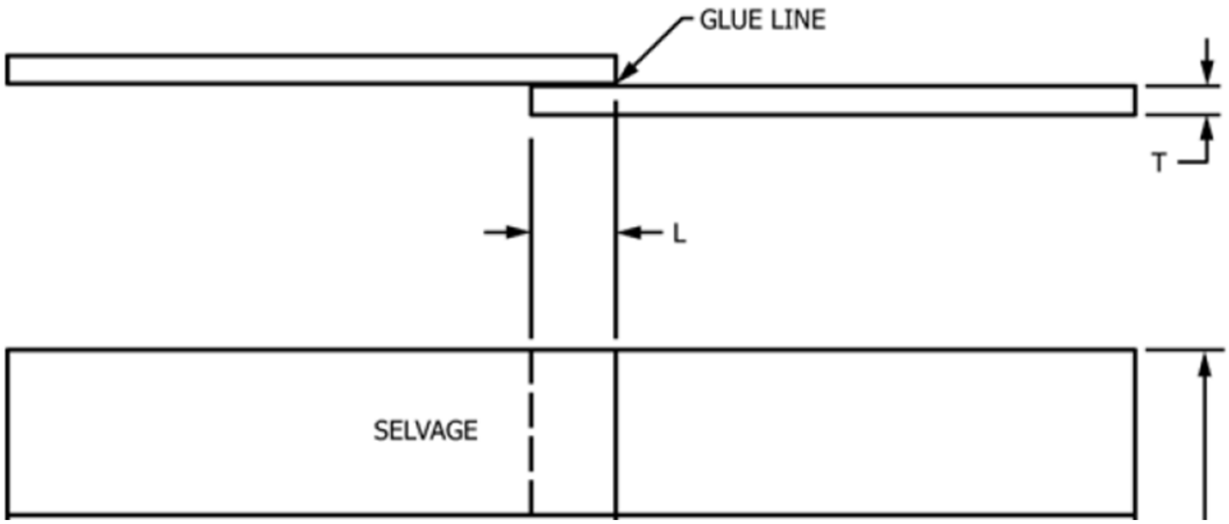

Figure 24: ASTM D 3163 Shear Test Coupon (Plastic)

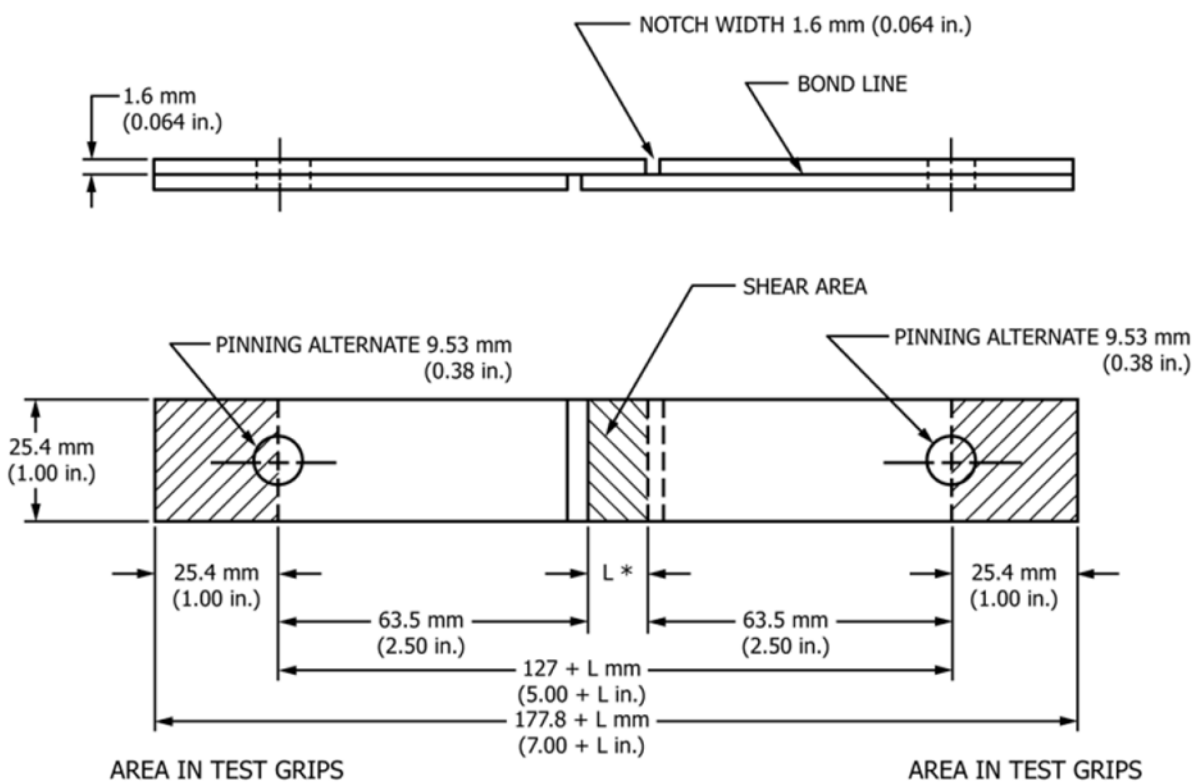

Figure 25: ASTM D 3165 Shear Test Coupon (Metal)

Excerpt from the MIL-HBK-5, regarding sample sizes for strength testing:

> "There are no universal "requirements" for sample sizes for basis values (allowables)[13]. The calculations can be performed on samples sizes as small as 3. The issue is what is acceptable to the organization or agency approving the basis values. To get metal material data approved for MIL-5/MMPDS, a minimum of 100 samples from 10 lots are required (though only for tensile strength, there are smaller sample size requirements for other properties), as quoted above by rp1957. For composite material data to be fully approved for Mil-17, a minimum of 30 samples from 5 batches is required for B-basis values and a minimum of 75 samples from 10 batches for A-basis values. In reality, the number of material batches in the dataset for calculating an allowable is much more important than the total number of samples, as the basis value is supposed to represent a defined point on the total material population distribution, and you want to be sure to account for batch-to-batch material scatter as well as test variability. The number of samples for an allowable also can vary with the particular approving agency's (FAA, Air Force, Navy, etc.) requirements and whims."

Further reading:

https://en.wikipedia.org/wiki/Sample_size_determination (wiki on sample size)
https://en.wikipedia.org/wiki/Strength_of_materials (wiki on strength of materials)

Statistics for Dummies, Rumsey (this was used as the textbook for one stats class I took)
Statistics II for Dummies, Rumsey
The Lady Tasting Tea, Salsburg (history of statistical methods for a general audience)
Statistics in Plain English, Urdan

Structures, Or Why Things Don't Fall Down, Gordon

The NFS *Wood Handbook* (available for free download:
http://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr190.pdf

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[13] Allowables are the test-defined strength of a material. That is: It is the stress that the material is "allowed" to go to in the design.