Two Bridges Built Using Black Locust Wood

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Summary

Two pedestrian bridges were recently built in New York using Black Locust wood, an unusual choice for a structural material despite its high strength, rot resistance, and local availability. The bridges explore the structural abilities of Black Locust, representing two very different bridge types. Squibb Bridge (an underslung suspension bridge) is built from short logs used in the round, with tubular steel connections. The TA Footbridge at Vassar College (a Town lattice truss) borrows from historic covered bridge technology, incorporating wooden peg connections. As Black Locust is naturally rot resistant, a cover is not necessary.

Limited information is available regarding the mechanical properties of Black Locust, and the species is unaddressed by the design codes and grading agencies. Load testing was performed using full-scale members and small clears in order to substantiate average values reported in the literature. Data is presented compatible with ASTM standards and NDS practices.

Guidance is provided for visual inspection, with attention to unsound knots, slope of grain, and Locust Borers. An inexpensive method for acoustic testing was developed for measuring modulus of elasticity and detecting voids, and could be further developed for timber grading at any mill.

Keywords: Black Locust, Town lattice truss, underslung suspension bridge.

1. Introduction

Although it is not considered a commercially important wood species in the United States, Black Locust (*Robinia pseudoacacia*) has some potential as a more sustainable alternative to tropical hardwoods. Namely, it grows locally in the northeastern U.S. (reduced transportation distance), it is naturally rot resistant (requires no harmful chemical treatment), and it is a nitrogen fixing plant.

Black Locust has some unique properties: it grows in knotty, twisty, small diameters, and it should be cultivated young, before it is attacked by locust boring insects. An efficient design can harness these characteristics. Black Locust is typically procured green. Careful detailing can be employed so that the material can season in place, eliminating the time and expense of kiln drying for some applications.

Black Locust timber was chosen because it is a durable, attractive, and naturally rot resistant wood, superior to pressure-treated lumber while non-toxic to the environment. This makes it a locally grown alternative to chemically treated lumber, endangered tropical woods, and decay prone woods. The fast-growth timber is used in small diameters, and has a smaller carbon footprint than steel or concrete.

2. Squibb Bridge

Squibb Bridge forms a functional link launching near the Brooklyn Heights Promenade, crossing

Fig. 1 Squibb Bridge: a) main spans assembled off alignment and erected with a single crane.

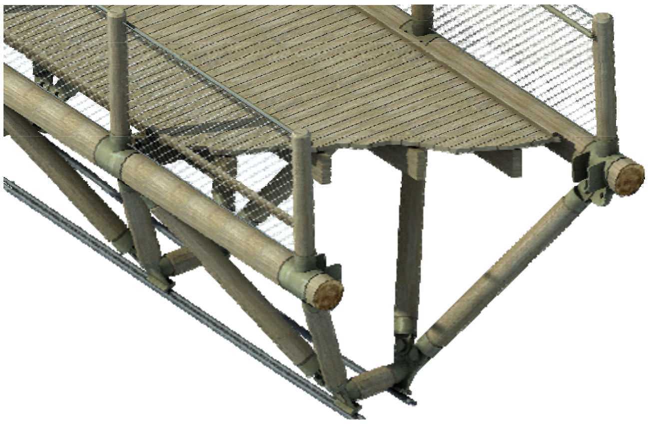

Fig. 2 Squibb Bridge: exploded view.

over Furman Street, and descending to the new Brooklyn Bridge Park along the East River. A design goal was to develop a bridge that is modest and that feels like it is part of the park, as opposed to a bridge in a park. Black Locust seemed to be an ideal choice – its tendency to darken, warp, and check as it seasons in place would create the sense of a weathered trail bridge.

The concept is an underslung suspension bridge composed of Black Locust timbers, and supported from below by a draped steel cable with props. The slender deck is just 25cm (10-inches) deep, with main spans up to 36.7m (120'-6"). To form continuous structural members the logs were turned on a lathe, and joined by steel pipe connections. The 150mm diameter (6"Ø) diagonal logs terminate in steel pipe fabrications, which are attached to the edge beams by bolted connections.

Bolted connections were designed to initially function as four bar linkages during fit-up, allowing the diagonal elements to be rotated into position and adjusted as required. Connection plates could be fabricated with a single bolt hole, the members could be assembled and adjusted as required, and the remaining bolt holes drilled to fit after completing the assembly.

After dry fitting the bridge spans, the timber-to-pipe connections were injected with a two part epoxy resin. The epoxy forms an integral structural connection by way of its bond strength, its compressive strength, and its confinement as it fills the annulus between steel and wood. Injection yielded mixed results, and is not easily inspected by the naked eye. By comparison, coating the ends of the logs with epoxy (buttering) prior to slipping them into the pipe could more reliably reduce the likelihood of forming air pockets within the connections, but would eliminate the adjustability of joints during fit-up.

Given the form of the bridge and the light weight of the wood, the main spans are quite flexible in the vertical and torsional modes, although measured vibrations are within the comfort criteria outlined by Sétra [17]. Horizontal vibrations are negligible.

3. TA Footbridge

The TA Footbridge at Vassar College in Poughkeepsie, NY is a Town lattice truss with Burr arch. It spans 16.4m (53'-8") over the Casper Kill Creek, connecting student apartments to the campus. The new structure was built to replace an existing bridge that had deteriorated and become unsuitable for pedestrian traffic. Existing abutments were reused with some modification in width to accommodate a roughly 2.4m (8 ft) wide path suitable for combined pedestrian and bicycle traffic.

The previous bridge was composed of two unpainted steel W10x45 beams with timber decking and railing mounted on top. The steel framing was perched a few feet above the creek, and had undergone severe section loss due to advanced corrosion of the unpainted steel exacerbated by seasonal use of de-icing salt. The old bridge developed a distinct sway that disturbed pedestrians, and an inspector recommended the permanent closure of the deficient span. Considering the history of corrosion issues, a solution using black locust members and connections seemed appropriate.

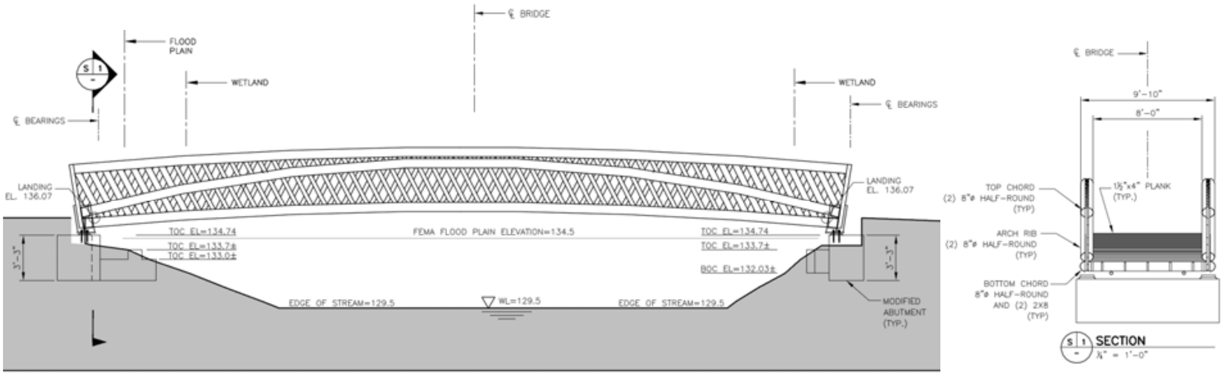

Fig. 3 TA Footbridge: Elevation & Section

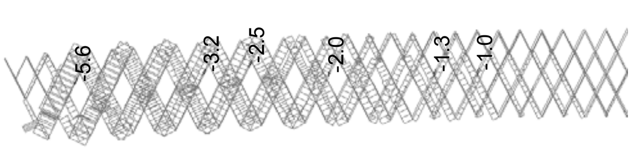

Fig. 4 TA Footbridge: F.E. model – Axial force in lattice members (kips) AASHTO STR-I combo

Fig. 5 TA Footbridge: F.E. model – Axial force in chords & arch rib (kips) AASHTO STR-I combo

The bridge adapts methodologies developed for covered bridges, however with the use of black locust, no cover is required (the cover serves to protect untreated timber from rot). The characteristics of a traditional Town lattice truss were appealing for a number of reasons. The lattice truss addresses a major shortcoming of other truss types, namely the lack of redundant load paths. Whereas typical truss bridges are highly non-redundant (i.e. all members are generally fracture critical), the lattice truss has a tremendous capacity to redistribute loads in the event of accidental loss of a member, and the lattice members serve as the web of a beam that is comprised of truss chords. Moreover, the TA Footbridge is detailed explicitly such that all members are replaceable in place. Town was successful in his original concept partly because of its extreme simplicity and economy, and in this case the bridge was built for about $1,819/m^2 ($169 / S.F.).

The principal advantage of a lattice truss is the use of small members and convenient framing, where the top and bottom chords are split in half and connected to either side of the lattice work. The chords need not be continuous, as long as the splices are staggered. The historical use of timber pegs (treenails) probably originated with ship building, was used in construction of Shaker furniture, and was adopted by Town again for its simplicity.

The burr arch serves as a redundant system whereby arch behavior is utilized to take best advantage of wood's high compressive strength. The bottom chord has a slight arch to mobilize compression behavior to the extent possible.

The top chord and arch members are comprised of 200mm (8") rounds cut in half and fastened on either side of the 50mm x 100mm (2"x4") lattice members. The bottom chord is comprised of a 200mm (8") round, cut in half, on the outside face and twin 50mm x 200mm (2"x8") members on the inside to support the 50mm x 100mm (2"x4") decking. The remaining framing for the deck are 100mm x 200mm (4"x8") joists, supported by joist hangers and span transversely with secondary 100mm x 150mm (4"x6") joists framing longitudinally.

Fig. 7 TA Footbridge: truss layout, assembly, and delivery (photos by Tim Leiching).

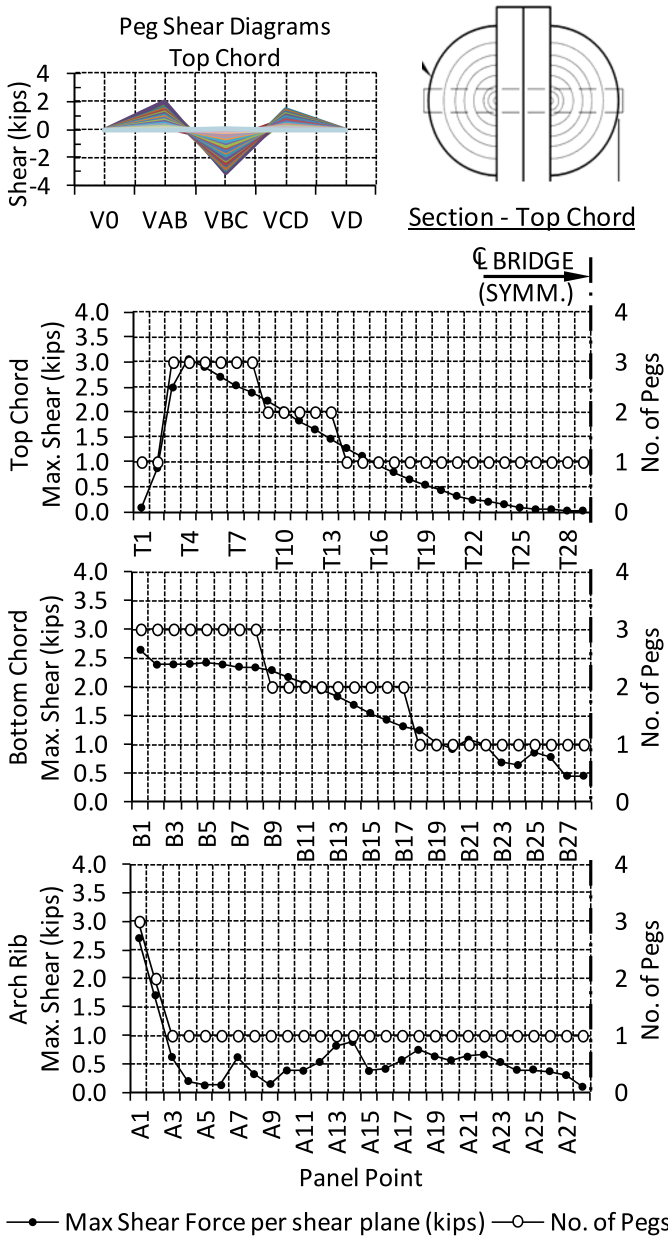

Figure 6 TA Bridge: maximum shear force per peg shear plane and no. of pegs at each panel point.

The use of timber peg connections presented some design challenges. Although treenail construction is ancient, it is unaddressed by the NDS and AASHTO design codes. Some load tests were performed in 1968 with full size joints with 50mmØ (2"Ø) White Oak trunnels for construction of the Union Street Bridge. The trunnels reportedly had ultimate strength of 106kN (24,000lbs) loaded in double shear [11]. Recent Timber Framers Guild guidelines provide comprehensive guidance for the design of mortise and tenon joints [18, 14], and with some modification was suitable to our purposes.

A useful scheme for truss fabrication is outlined by Graton [11]. The trusses were assembled in the shop by laying out the timber members on a level area. Chords were laid out with their natural sweep oriented in the direction of the bridge camber. The chords, diagonals, and arch ribs were clamped together, but within days the timber had moved significantly as the wood began to dry. In lieu of clamps, a single decking screw was temporarily installed in a pre-drilled hole at each peg location along the top and bottom chords. Over-fastening was an effective means of controlling the movement of the green timber.

With the trusses firmly clamped together, the holes for the timber pegs could be drilled. It was unclear what size holes to drill for the 31.8mm (1¼") diameter pegs, given the movement of the wood with changing moisture content. Metalworking bits were used such that hole diameters could be adjusted as needed in 0.4mm (1/64") increments. Pegs were driven using a 7kg (16 lb) hammer and a steel driving cap sized to prevent over-driving the pegs beyond flush. Based on Graton's description, we determined that if the holes are properly sized to match the pegs, each hammer blow should drive the peg about 12.5mm to 25mm.

The bridge halves were then raised into the vertical position after securing the bolted and peg connections, and the joists were installed using off-the-shelf face mount joist hangers. The completed span was shipped to the site on the back of a truck and erected using a single crane. Decking planks were installed on site, reducing the shipping and lifting weight of the span, and providing access to install conduit from above.
While we did not have the ability to control moisture content of the bridge members (wood was delivered green), the pegs were kiln dried – a combination that can be favorable in service, as the seasoning of the bridge members will cause the holes to shrink and tightly grip the pegs over time.

On subsequent inspection, the bridge is stiff and robust. Checking has begun for the exposed top ends of the lacing members. Small patches of mold were observed in three locations where a small skin of sapwood remains on the members. In time, the sapwood will naturally fall off, leaving only the heartwood, which is not hospitable to mold growth. Rather than waiting, the sapwood can be scraped or sanded down to heartwood.

4. Some Characteristics of Black Locust

Black Locust has been used by others for ship building, fire wood, and animal fodder. It is native to the U.S., and since the 1600's has been cultivated in Eastern Europe, France, Korea, China, and India [12]. It forms 23% of forested area and 19% of annual timber output in Hungary [16]. Significant differences have been reported within the species, and in particular Shipmast Locust is known to grow extensively in the Hudson Valley and on Long Island in New York [15]. Black Locust is attacked by Locust Borers (*Megacyllene robiniae*) in the U.S., but not Europe.

Fig. 8 Locust Borer (Megacyllene robiniae). [13].

The *Wood Handbook* indicates average values for strength, density, and modulus, which appear to be based on testing performed during the 1920's. Since then, the character of timber stock in the U.S. has changed substantially [9]. Recently, some demonstration projects have used small diameter Black Locust logs [1, 8], though there does not appear that any rigorous testing program has been performed to establish the statistical strength characteristics of the species. There seems to be little precedent in terms of its structural use in the U.S.

Black Locust has been cultivated extensively in Hungary, where it is used for glulam beams, residential housing, tool-sheds, fence components and panelling. One could presume there must be a trove of information on the mechanical properties available in the Hungarian language.

4.1 Experience of Others

With the idea that practical experience can be at least as valuable as research reports, we reached out to local professionals with experience using Black Locust – a timber mill, a trail bridge builder, and a wood specialist. Their works have included boardwalks, small trail bridges, fences, park furniture, and sculptures. They provided some useful guidelines for using Black Locust.

Black locust is typically procured in green condition, as the trees are generally cut down on demand. Lead time varies significantly depending on accessibility of the tree stands in the given seasonal conditions (snowfall, mud, etc.). The wood is typically used in its green condition, and allowed to season on place. In its green state, it is considerably weaker than the reference values at 12% MC (see Table 1), thus structures built using green wood are weaker at the beginning of their service life, and get stronger over time. In the absence of better test data, it has been suggested to use the published design values for White Oak.

Table 1 Ratios of dry to green clear wood properties as reported by ASTM D2555 [5]

Modulus of Rupture	Modulus of Elasticity	Compression Parallel to Grain, Crushing Strength
1.40	1.11	1.50

Seasoning can cause the wood to warp, twist, check, and split. It can take up to three years to season in place, and in that time the movement of the wood can be significant enough that it has been described as behaving like it is still alive. Conventional wisdom is that overfastening is the key to managing twisting and warping, and our experience so far has corroborated this advise. To reduce checking, the ends of members can be treated with an aqueous wax sealer (such as Anchor Seal). Some checking and splitting is unavoidable if the wood is allowed to season in place, and some kiln dried decking planks have reportedly warped and checked considerably despite efforts to control it.

Inspection of the source wood can be difficult. Locust Borer larvae burrow inside the logs and can hollow them out without leaving a sign other than a small entry hole, which is easily concealed by the bark. The wood species is not addressed by any American grading agencies, and for this reason at least one local mill would not supply wood for the projects knowing that it would be used for bridge construction.

5. Establishing strength characteristics

A robust testing program seemed like a sensible approach to establishing design values for the project-specific wood sources. For each of the two bridges, a testing program was implemented to substantiate key design and procurement decisions. No attempt was made to perform a statistically robust program to characterize the mechanical properties of the entire species, so the data should be examined critically and carefully before contemplating its use for a different project. Indeed, the testing uncovered significant differences in the strength of wood used for the two projects. Wood was tested in its green state to establish conservative lower bound mechanical characteristics, consistent with the condition of the bridges at beginning of service life.

5.1 Testing Regime

The bridges were constructed independently by two different contractors. For Squibb Bridge (Block A), the contractor procured and milled most of the wood in his own shop. Logs were reportedly cut from trees near the New York – Pennsylvania border. For the TA Footbridge (Block B), wood was prepared by a mill, and the source location was not reported.

Initially, a few small clear specimens were cut from a log selected to be representative of the logs at the mill (Block 0), and were tested at the materials testing lab at New York City College of Technology, CUNY. Testing flexure and compression parallel to the grain demonstrated the general strength characteristics of the species, and helped to qualify the material that the timber mill could produce. While the Block 0 specimens tested below the published average values of Black Locust, they were superior to White Oak.

Table 2 Compression Test Data: In Block 0 a few small clears were tested to qualify the wood produced by the mill. Block A is selected to be representative of the timber used for Squibb Bridge. Block B is selected to be representative of TA Footbridge.

Compression Parallel to Grain		n	Ultimate Compressive Strength			Modulus of Elasticity		Moisture Content		Density		Specific Gravity	
			Mean (ksi)	COV (%)	PTL	Mean (ksi)	COV (%)	MC (%)	COV (%)	Mean (pcf)	COV (%)	Mean	COV (%)
FPL White Oak	Green	20	3,560	18	2,321	1,250	22	Grn				0.60	10
	12%	20	7,440	18	4,851	1,780	22	12				0.68	10
FPL Black Locust	Green	20	6,800	18	4,434	1,850	22	Grn		58		0.66	10
	12%	20	10,180	18	6,638	2,050	22	12		48		0.55	10
Block 0	Small Clears	2	6,582	2.6	6,037	2,011	14.6						
Block A	Small Clears	45	5,219	12.2	4,051	1,770	16.2	24.8	17.0	47.9	5.4	0.61	4.1
	150mmØ x 1.83m logs (6"Ø x72")	10	4,107	18.4	2,518	1,765	21.3	32.3	25.9	60.0	16.5	0.73	5.4
Block B	Small Clears	41	7,156	20.8	4,424	1,327	49.5						

A second round of testing (Block A) involved a large batch of small clears tested in flexure and compression, as well as several full size members loaded to failure [4]. We performed compression testing on 10 logs approximately 150mmØ x 1.83m long (6”Øx72”) diameter with natural taper and curvature. Flexure testing was performed on five rough sawn beams 50mm x 200 mm 2.49m long (2”x8”x98”) and on five beams 100mm x 267mm 2.49m long (4”x10 ½”x98”).

Block B consisted of 41 small clears loaded in compression parallel to the grain. The specimens were cut from samples taken from the stack of wood in the shop, selected to be representative of the wood used on the bridge. Test data are presented in Tables 2 and 3.

Table 3 Flexure Test Data: See caption for Table 2.

Flexure		n	Modulus of Rupture			Shear Parallel to Grain			Modulus of Elasticity		Density		Specific Gravity		Moisture Content	
			Mean (psi)	COV (%)	PTL	Mean (psi)	COV (%)	PTL	Mean (ksi)	COV (%)	Mean (pcf)	COV (%)	Mean	COV (%)	(%)	COV (%)
FPL White Oak	Green	20	8,300	16	5,733	1,250	14	912	1,250	22			0.60	10	Grn	
	12%	20	15,200	16	10,499	2,000	14	1,459	1,780	22			0.68	10	12	
FPL Black Locust	Green	20	13,800	16	9,532	1,760	14	1,284	1,850	22	58		0.66	10	Grn	
	12%	20	19,400	16	13,400	2,480	14	1,809	2,050	22	48		0.55	10	12	
Block A	Small Clears	45	11,249	14	8,380				1,542	14.9	47.3	6.4	0.61	6.8	24.6	18.2
	50mm x 200mm x 2.49m	5	10,174	8.7	7,993	650	8.9	507	1,705	4.6	48.7	4.9	0.65	9.5	32.1	6.4
	100mm x 267mm x 2.49m	5	7,552	33.6	1,300	638	33.5	111	1,625	7.9	56.2	3.8	0.68	5.9	36.5	3.8

5.2 Yellow Black Locust, an unnatural selection, and clearly unclear clears

The two blocks of tests were intended only to characterize the material used for their respective projects, but it is tempting to wonder whether a meaningful comparison could be made between the data sets for small clears loaded in compression parallel to the grain (Table 2). In terms of statistical rigor, the body of data could seem almost like a disaster. Samples were not randomly selected, nor were they selected to be representative of the species [7]. Block B specimens were rough sawn, and were not planed down to the exact dimensions normally required [3]. Though clear specimens are typically required to be free, or practically free, of all blemishes or defects, several of the test specimens exhibited checking, splitting, knots sound and unsound, discoloration, sapwood, mold spots, and Locust Borer holes.

From the context in which the test blocks were envisioned, these characteristics are suitable. The selection was intended be representative only of the wood used in construction of the two bridges.

Despite the sampling anomalies, some interesting information can be inferred by comparing the two

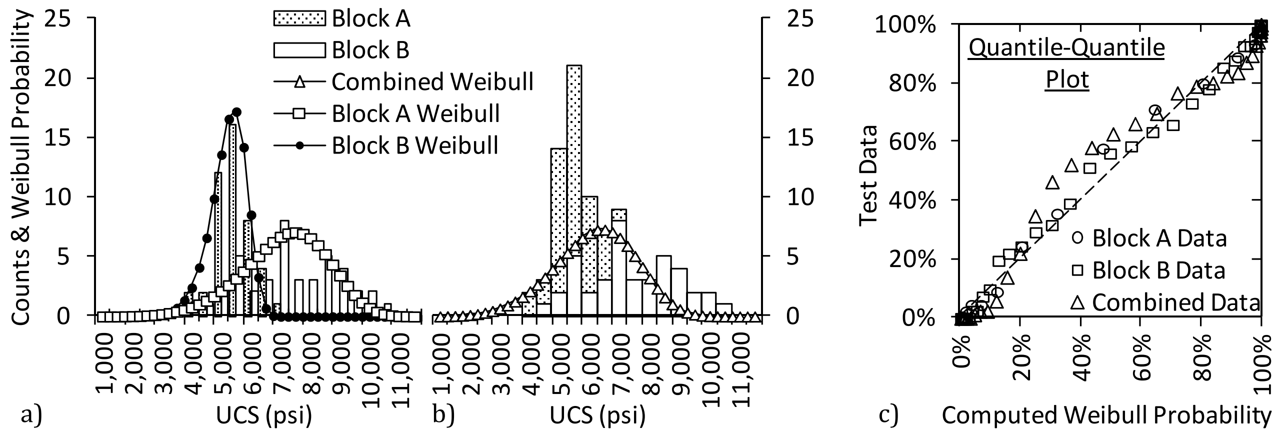

Fig. 9 Test data for small clears loaded in compression parallel to the grain: a) Block A and Block B data, with Weibull pdfs, b) combined data with Weibull pdf, c) Quantile-quantile plot illustrates a relatively poor fit for the combined data.

blocks of data. Compared to Block B, Block A exhibited a smaller mean strength and lower COV. Lower 5% one-sided confidence limits were computed at 75% confidence in accordance with ASTM D2915 [6], also referred to as the parametric tolerance limit (PTL). Despite having fewer samples and higher COV (broader spread of observed UCS), Block B has a higher PTL, and thus a higher design strength could have been used for TA Footbridge as compared to Squibb Bridge. Though the ASTM standard uses a normal distribution for computing the PTL, Weibull distribution is generally considered a better fit, and is used as the basis for calibrating Eurocode design values. A Weibull probability distribution function was fitted to each data set, shown in Fig. 9.

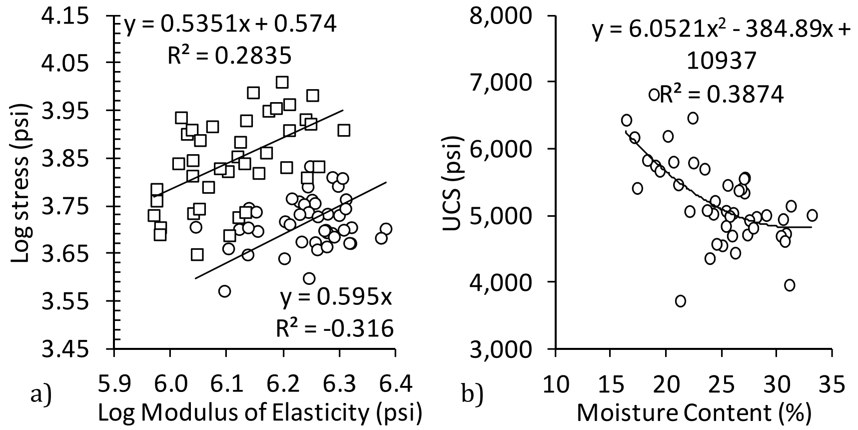

Fig. 10 UCS Relationships: a) ○ Block A and □ Block B MOE vs. UCS, b) Block A MC vs. UCS.

Block A specimens were tested at an accredited laboratory in accordance with ASTM D143 [3]. Moisture content and specific gravity were not measured for Block B specimens, since the samples were taken directly from the stack of wood used on the bridge, and the wood in service would never be greener than the samples. In both test blocks, the wood was considered green, as the specimens were freshly sawn from recently felled logs.

The character of the samples visibly differed. Block A was reddish brown heartwood, whereas Block B was bright yellow heartwood characteristic of Shipmast Locust, also called Yellow Locust. The production timber associated with Block B is generally straighter grained, with fewer and smaller unsound knots, also consistent with Shipmast Locust.

6. Visual inspection, acoustic testing

A major challenge was establishing quality control standards for an unusual wood species, particularly for small diameter logs. Existing log grading guidelines that we are aware of [20] penalize small diameter logs for their modest yield at the mill, and could not be used directly for a project that specifically intends to use small logs. For rail bridges, AREMA (7-1.2.1) permits use of hardwoods complying with the requirements of the Northeastern Lumber Manufacturers Association. NELMA does not address Black Locust. Several state DOTs allow wood to be used based solely on the Engineer's visual inspection. For awhile, it seemed we were out on a limb.

6.1 Visual Inspection

Visual inspection is the primary means of ensuring a quality product. ASTM D25 offers guidance for inspection of round timber piles, and was an excellent basis for a visual inspection program that could be tailored to Locust's peculiarities.

Unsound Knots (or rotten knots) are essentially a spongy void, and can severly limit the load carrying capacity of a member. In the Block B tests, two specimens with soft knots buckled under considerably lower loads than the clears, whereas specimens with sound knots were virtually indistinguishable from the clears.

Sound knots were limited to 20mmØ (¾"Ø), 13 per meter (4/foot). In practice, this was not achievable for Squibb Bridge, and unsound knots were scraped out and repaired with epoxy. The *Timber Bridges Manual* offers guidance on epoxy repair and coring of timber members.

Slope of Grain weakens timber, and Hankinson's formula is deeply embedded in the NDS code and standard practices for assessment of historical timber structures. Given the twistiness of Black Locust, the strength of rough sawn and round turned members could be affected by excessive slope of grain, and for Squibb Bridge at least one edge beam was rejected on this basis. Slope of grain was limited to 1:6.

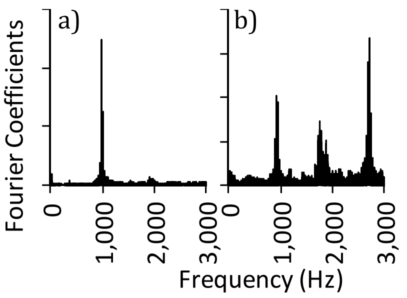

Fig. 11 Stress Wave Frequency: a) Typical log specimen with one frequency response, b) Rejected log specimen with three frequency responses as stress wave partially reflects off of large internal imperfections.

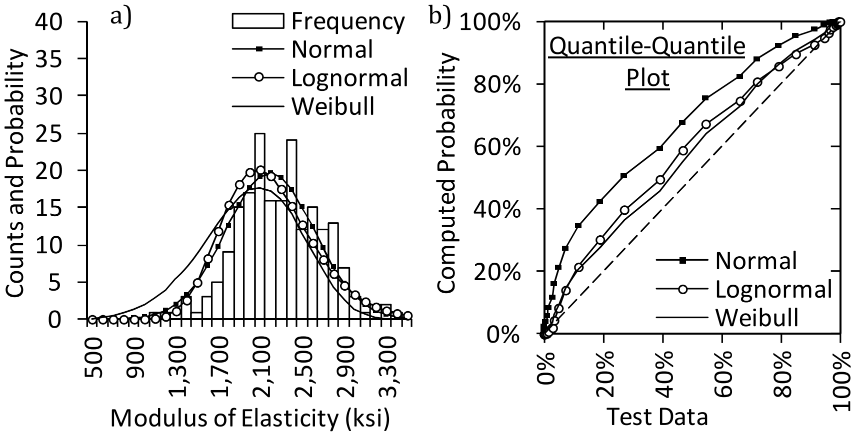

Fig. 12 Acoustic test data for logs: a) Block 0 data with Weibull pdfs, mean 2,264ksi, COV 20.3%, b) Quantile-quantile plot suggests Weibull distribution is suitable for the combined data.

6.2 Acoustic Testing

The relationship between Elastic Modulus and stress wave velocity has been known at least since St. Venant's experiments [19], and is well established in the literature [10]. When a specimen is struck with a hammer at one end, a stress wave travels along the axis of the specimen at a velocity that is related to the stiffness and the density of the material. The stress wave can be registered as a vibration and as an audible percussive sound. When the stress wave (sound wave) reaches the opposite end of the specimen, it is reflected off of the face, and returns to the struck end, and is reflected back and forth for several cycles. The MOE can be computed as:

$$\mathrm{MOE} = \rho \cdot V^2 \tag{1}$$

A similar approach is used for pile integrity testing to reveal internal voids or weaknesses otherwise uninspectable. This ability could be particularly useful for detecting voids carved out by Locust Borers, and could be adapted to identify and even locate the position of defects in logs.

where:
MOE = modulus of elasticity
ρ = density
V = velocity of stress wave traversing axis of specimen $= 2 \cdot L \cdot f$
f = frequency of stress wave reflecting from end to end

While some commercial products are available for measuring the stress wave velocity, they were beyond the reach of this project. A homemade approach was taken to develop an acoustic testing methodology capable of achieving high precision results as inexpensively as possible, using readily available equipment.

The setup consisted of:

- A laptop computer
- Inexpensive ($5) headphones (JVC model HA-FX8-B)
- Adhesive tape, measuring tape, and a strong scale

Computers typically process sound at a frequency of 44,100Hz (sampling rate), and when plugged into a microphone jack typical headphones can capture soundwaves at pitches up to 22,050Hz with sensitivity of 101dB / 1mW (thus calibration frequencies of up to 8,200Hz for steel specimens were well within the Nyquist frequency of the system). Accuracy of the setup was compared to a professional musician's electronic tuning device. Measured frequencies were in agreement ±1Hz. Software was written to record the soundwave, process it using a Fast Fourier Transform, and detect peak frequencies (f). Length, diameter, and weight were measured the hard way (L and ρ).

Concurrent with Block 0 mechanical testing, acoustic testing was performed on 207 logs at the mill, with the aim of capturing elastic modulus data representative of the population of logs used for Squibb Bridge. Test data are presented in Fig. 12, alongside the computed Weibull distribution. Voids were successfully detected by the software as having more than one strong frequency peak. UCS relationships from testing of small clears could be used to relate acoustic elastic modulus to the strength, and adjusted for moisture content (Fig. 10).

7. Discussion, Conclusions and Acknowledgements

The research comprises contributions of several individuals. Block A testing was performed under contract at the AEWC, University of Maine by Russell Edgar and Jon Hill. Block B testing was done at New York City College of Technology, CUNY with assistance from Dario Feliciangeli.

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