Bugatti 100P Structures

The Bugatti 100P Airplane

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(An independent study performed in support of the construction
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Abstract

The Bugatti 100P was a balsa-cored, hardwood-skinned, largely monocoque-structured race plane developed and designed by Bugatti and de Monge in 1937. A patent was awarded on the novel construction technique, which employed available woods including balsa and poplar and furniture-making skills and tools. The aircraft was built in a Parisian furniture factory.

In this paper, we study the aircraft structures pertaining to the new construction. While the Bugatti 100P replica aircraft is lighter than the original, it is not a lightweight aircraft, but it is shown to be a strong and adequate structure relative to expected loading.

Introduction and History of the Bugatti 100P

Louis de Monge was a successful French/Belgian aircraft designer and engineer. Family photographs show de Monge and his brothers with aircraft of their own designs as early as 1906. He is characterized in the British weekly Flight as the "famous French aircraft designer" in 1924. At least one of his designs from the 1920s used small, Bugatti-built engines.

In the late 1930s, Ettore Bugatti asked de Monge to design a race plane around Bugatti's successful auto engines. The plane was to be built in Paris of mostly indigenous woods, in a converted furniture factory, as quickly as possible. De Monge took an office in the factory, nearby the plane, and construction began in 1937.

The original 100P never flew, its development interrupted by the start of World War II. The plane – disassembled and hidden in a barn near Paris – survived the War but was not rediscovered until the late 1960s. During some periods, the airframe was stored outdoors and exposed to weather. Now cosmetically restored, it is on display at the Experimental Aircraft Association in Oshkosh, Wisconsin, USA. The remaining strength of the aging wooden structure is unknown and it is not considered flight worthy.

Our team is constructing a flying replica faithful to the original Bugatti 100P aerodynamically and structurally, with concessions to modern safety.

Methods and Materials

Methods

The original Bugatti fuselage was constructed by gluing and fastening many pieces of thin hardwood in straight sections between frames. Pieces of balsa wood were then glued to the outside and sanded into the net shape. It is not known whether the balsa fibers were oriented orthogonally to the surface or longwise, but the latter is likely. Current practice in cored laminate construction is to orient the balsa fibers perpendicular to the skins so that the compression and shearing forces correspond to balsa woods strengths. This is the method we use in the new construction.

Finally, the original Bugatti received a thin external hardware skin glued and fastened over the balsa core, then covered linen and dope. The built-up construction of the original airplane resulted in thicker skins mid-way between frames, since the insides surfaces were straight and the outsides surfaces aerodynamically curved. While this would all strength to loads perpendicular to the skin (oil-canning type loads) and between frames, it adds little to the overall strength of the structure, since the thinnest parts of the skin are most highly loaded fuselage bending or torsion.

Materials

The new 100P uses modern epoxy adhesives and a modern boat-building material with identical make-up called Durakore. Durakore employs a balsa wood core, with thin hardwood skins, factory-glued under controlled conditions, and with pre-scarfed ends. Durakore arrives in planks that may be sawn into strips and joined end-to-end in long strips. Our construction employed strip-planking (a boat-building technique for complex hulls), where strips are edge-glued around disposable forms. After the forms are removed, the remaining monocoque hull is then glass inside and outside and permanent bulkheads, doublers, and mounts installed.

Essentially, the structure is identical to the original aircraft with minor differences. The new structure is constant in thickness in all places (except where doublers may be installed), and substitutes gap-filling epoxy adhesives instead of resorcinol or other glues from the 30's requiring very thin glue lines. Also, in a concession to safety, fiberglass fabrics are used instead of canvas to add to the margin of safety. The modern structure will be lighter, and stronger.

Other structures are formed from poplar, Sitka spruce, aircraft birch plywood, and Douglas fir plywood. Typical strengths of the materials are noted.

Figure 1 Durakore

MATERIAL COMPARISONS	Weight (kg/m²)	Deflection (mm)	Pressure to Failure (kPa)
19mm DuraKore/ T750 each side	7.6	3.2	38
19mm Cedar / T750 each side	9.5	3.2	37
13mm Plywood	8.1	7.4	5
Solid Layup 9x C600+M225	31.4	9.5	30

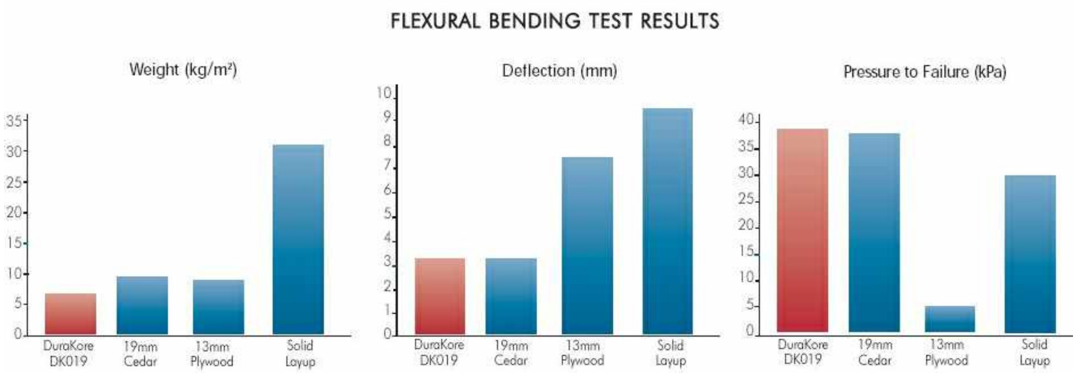


Figure 2 Durakore Material properties (Source: www.atlcomposites.com.au)

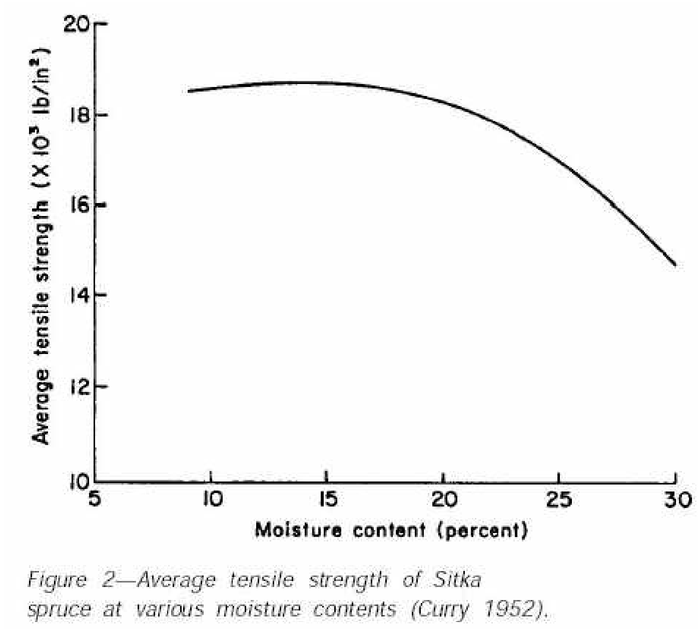


Figure 3 Strength of Sitka Spruce (USDA Forest Service FPL-RP-497)

Figure 4 Strength of Aircraft Birch Plywood (source)

Figure 5 Strength of Douglas Fir Plywood (source)

Mechanical Properties (2-inch standard)

	Specific gravity	MOE x10^6 lbf/in^2	MOR lbf/in^2	Compression		WML[a] in-lbf/in^3	Hardness lbf	Shear lbf/in^2
				Parallel lbf/in^2	Perpendicular lbf/in^2			
Green	0.40	1.22	6,000	2,660	270	7.5	440	790
Dry	0.42	1.58	10,100	5,540	500	8.8	540	1,190

[a]WML = Work to maximum load.
Reference (59,98).

Figure 6 Strength of common Yellow Poplar (USDA Forest Service fact sheet)

Stabilizer Strength

Structure

The 100P v-tail horizontal stabilizer is supported by two box spars joined and further strengthened by a monocoque skin. Each spar is constructed of a pair of 1 x 1.5 inch Sitka spruce beams boxed by 1/8" spar-grade birch plywood. The box spars taper towards the ends and are joined by a Durakore plank running lengthwise on the top and a second Durakore plank running lengthwise along the bottom. The Durakore planks will be further supported by periodic bulkheads (ribs) of Durakore, and all epoxy glued.

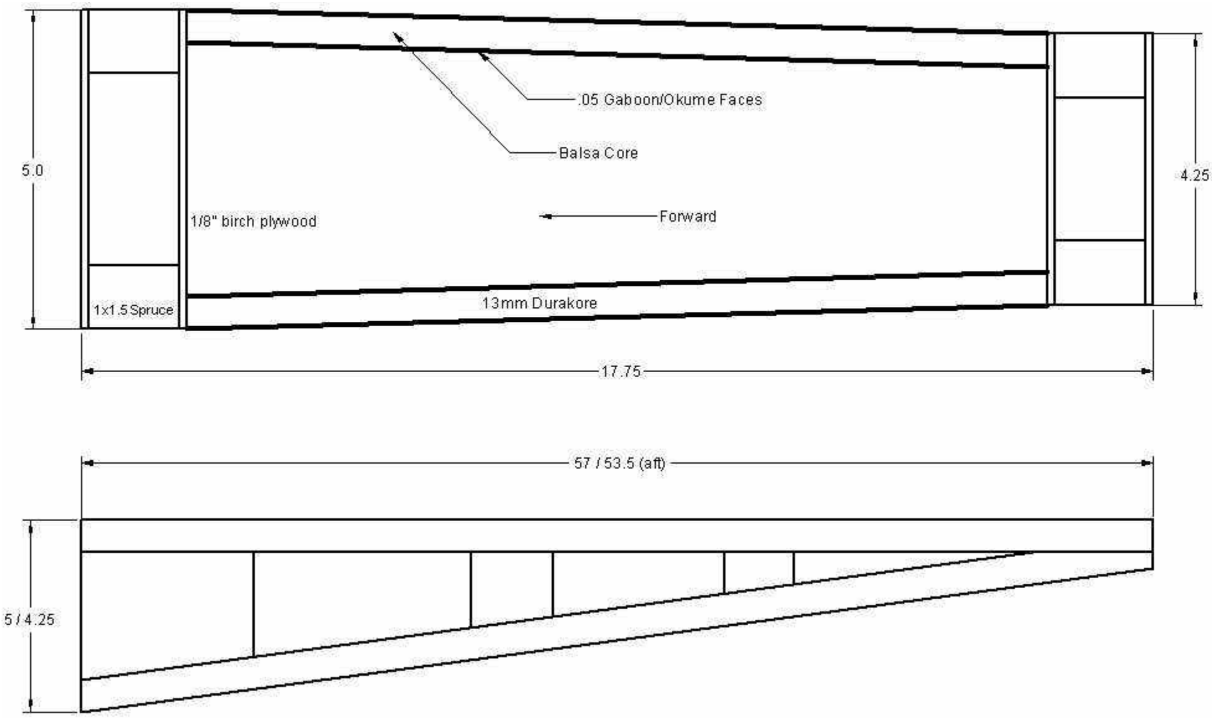


Figure 7 Bugatti Horizontal Stabilizer Spar Detail, with spacer blocks

Bending Moment

Wood is an elastic and brittle material, with little or no yield until ultimate failure. Woods are difficult to fixture in pure tensile testing, and so are normally tested in bending and rated for strength under stress by modulus of rupture or bending strength. Depending on quality and placement of flaws, wood subjected to pure tension may fail at lower values than bending since all flaws are equally loaded throughout the member.

The cantilevered spar is constructed of 4 types of hardwoods of differing stiffness, creating an *indeterminent structure*. Important material properties, including ultimate strength in tension and compression, and modulus of elasticity (stiffness), for the various woods are conservatively estimated from various sources and summarized:

Material	$\sigma_{u,c}$, psi	$\sigma_{u,t}$, psi	*E*, mpsi
Sitka Spruce	5610	10,200	1.57
Okoume/Gaboon	3900	7300	1.14
Birch	8170	16,600	2.01

Table 1 Strength of Materials

The Durakore panels also contain end-grain balsa oriented perpendicular to the face, so that in tension or compression along the length of the plank, the balsa wood is loaded itself perpendicular to the grain. Balsa offers only 118 psi of ultimate strength in this direction, so it's contribution to the strength of the structure is negligible. It should be noted, however, that it does contribute significant strength to aerodynamic loads on the surface of the wing.

The structure is analyzed for failure at the center line of the aircraft – the thickest part of the stabilizer wing, where it joins the other half of the wing, and the tallest area shown on the left side of Figure 7. The area moments of inertia of the structures cross-section at that point are calculated for each component, with the slightly tilted Durakore skins taken at an average centroidal distance but analyzed for stress at the farther distance from the neutral bending axis:

Component	Base	Height	Distance	I_c ($bh^3/12$)	Ad^2	$\mathbf{I_{TOT}}$	c
Fore spruce	1.5	1	2	.125 ea	6 ea	**12.25**	2.5
Fore caps	.125	5	0	1.3 ea		**2.60**	2.5
Aft caps	.125	4.25	0	.80 ea		**1.60**	2.125
Aft spruce	1.5	1	1.625	.125 ea	3.96 ea	**8.17**	2.125
Top skin	14.5	.05	2.32 ave	.0002 ea	3.90 ea	**7.81**	2.5
Inside skin	14.5	.05	2.06 ave	.0002 ea	3.08 ea	**6.16**	2.5

Table 2 Area Moments of Inertia

So,

I_{xx} = 20.4$_{spruce}$ in^4 + 4.20$_{birch}$ in^4 + 14.0$_{okoume}$ in^4 = 38.6 in^4

In elastic bending, plane sections remain plane, and in a symmetrical beam, the neutral axis lies down the centerline:

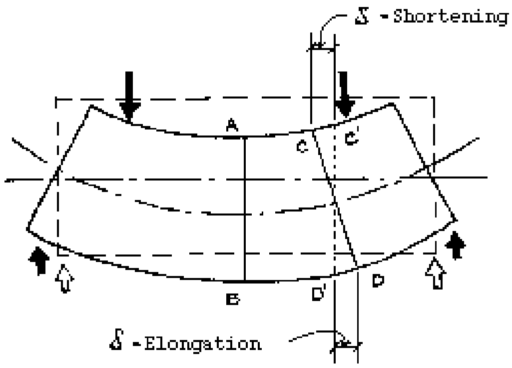


Figure 8 Bending of a beam

with stress, strain and modulus of elasticity related by:

$$\sigma = E\varepsilon \tag{1}$$

and stresses in bending of the cantilevered spar given by:

$$\sigma = \frac{Mc}{I} \tag{2}$$

The first step to analyze the strength of the spar is to guess at which material might fail first, strain it to failure, and then check the other members for premature failure. The okume skins at 2.5 inches from the centroid might fail first since they are weaker in strength (even though less stiff). Using equation 1 and the modulus for okoume:

For tension: $$\varepsilon_{y=2.5} = \frac{\sigma_{u,t}}{E} = .0064 \tag{3}$$

For compression: $$\varepsilon_{y=2.5} = \frac{\sigma_{u,t}}{E} = .0034 \tag{4}$$

Since plane sections remain plane, the strain distribution is linear, from zero at the neutral axis to maximum at c_{max} so the maximum strain for each element is easy find as a ratio of c's. In the spar of interest, each element has c=2.5. So, using equation 2 and the strain for failure of the okoume, check the other elements for stress failure:

Spruce: $\sigma_t = E\varepsilon = 10{,}048 psi$ <10,200 psi

$\sigma_c = E\varepsilon = 5371 psi$ <5610 psi

Both values are less than the strengths for spruce, so the spruce could not have failed. Also, since the stress values are close to failure, it is also indicates the structure is well balanced.

Birch: $\sigma_t = E\varepsilon = 12{,}864 psi$ <16,600 psi

$\sigma_t = E\varepsilon = 6834 psi$ <8170 psi

The birch plates will not have failed either, and are also well loaded.

The load, or bending moment supported by each element of the indeterminent structure sum to a total load carried by the structure until the first element fails (the okoume skins), and the structure weakens:

$$M_{okoume} + M_{s.spruce} + M_{birch} = M_{total} \quad (3)$$

Solving equation 2 for M and inserting the state of stress for each element at the current strain state, and including the values of I and c for each, gives a moment supported by each element at failure of the okoume:

Elements	M_t, in-lb	M_c, in-lb
Okoume	40,880	21,840
s. spruce	82,394	44,042
Birch	21,612	11,481
Total	144,886	77,363

Failure of the wing spar occurs at 77,363 in-lbs load when one side of the spar fails under compression.

Wing Loading

FAA Advisory Circular 23-19A, AIRFRAME GUIDE FOR CERTIFICATION OF PART 23 AIRPLANES, provides for air loading on untwisted, high-taper wings as a simple Planform loading (especially for horizontal tails), where load is directly proportional to chord variation. Planform loading is assumed unconservative for wing taper ratios (tip chord / root chord) less than .25, but conservative for taper rations greater than .35.

Since the 100P horizontal stabilizer is strongly tapered from root to tip - essentially triangular in planform,

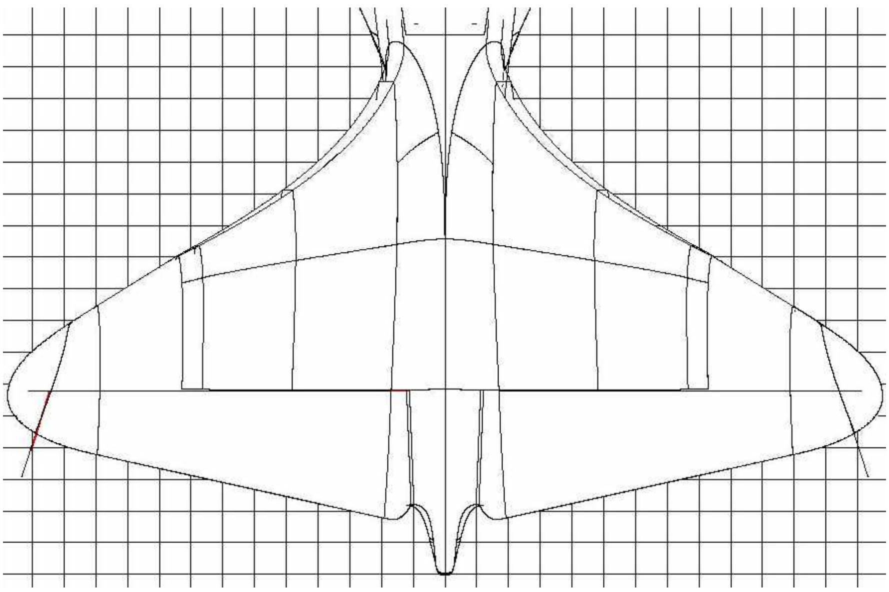
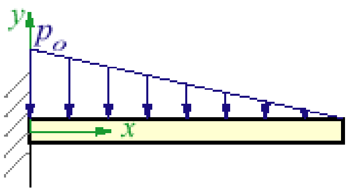


Figure 8 Bugatti Tail Planform

the aerodynamic load under planform distribution would closely approximate a triangular loading on the wing spar:



$$M_{max} = M(0) = \frac{L^2 p_0}{6} \qquad (4)$$

Figure 9 Cantilevered Beam in Triangular Loading (www.efunda.com)

Solving for the load factor p_0, the reaction is calculated as the maximum shear load:

$$V_{\max} = V(0) = -\frac{L\ p_0}{2} \qquad (5)$$

Each half of the horizontal stabilizer wing supports **4072 lbs** when M=77,363 in-lb.

The taper ratio is difficult to determine for elliptical wings, but is estimated to be about .3.

Flight loads and Safety

Aircraft flight loads for light airplanes range from -1.5g to +3.8g, and in aerobatic airplanes, from -3g to +6g. Normal flight loads for rear-tailed aircraft are downward.

The Bugatti replica will weigh about 3000 lbs, with normal tail loads estimated at about 10% of the total weight (typically 6-8%)1, downward, or about 300 lbs. Standard category loading at +3.8g increases the load to 1140 lbs, with a safety factor of 1.5 increasing the tail flight load to 1710 pounds. At 2 x 4072 lbs, the Bugatti horizontal stabilizer spars support loads well in excess of the worst case flight loads.

Effect of Glass Skins

The Bugatti stabilizer will be fiberglass-covered for further strength, but adds additional complexity for analysis.

Fiberglass fabric and epoxy have a modulus of about 2.52 Mpsi, an elongation at breakage of 1.98%, and a tensile strength of about 45,870 psi according to testing by the Fibre Glast Corp. The tensile strength of a glass composite is dependent on the epoxy/glass ratio, itself highly variable with application technique. Since, the composite thickness can't be known precisely with hand layup, tensile strength (per unit area), are unreliable. For that reason, glass fabrics are often rated in breaking strength per unit width.

At elongations for glass failure of ε=.0198, the wood members are well past ultimate strengths, so contribution to strength of the glass element can be estimated at the strains used for failure of the first wood element. A ε_t=.0064 and ε_c=.0034, where Okoume failure occurs, the stress in the glass is,

$$\sigma_t = E\varepsilon = 16{,}128\,psi$$

$$\sigma_t = E\varepsilon = 8568 psi$$

However, forces and moments can't be resolved without know the thicknesses, but since we have an elastic material and know the breaking strength per fabric ply – inch, and simple ratio of strains will yield a force applied by the fabric, per inch width, at the given strain. Our chosen fabric has breaking strengths of 330 lbs/inch in one direction, and 350 lbs/inch in the other, so we choose the smaller of the two:

F_t = 330 * .0064 / .0198 = 107 lbs / inch

F_c = 330 * .0034 / .0198 = 57 lbs / inch

Several assumptions must be made to complete the estimate of the strength contribution of the glass reinforcement. Most importantly the glass web should be properly anchored at the centerline of the ring, ideally continuing unbroken from one side of the in to the other, especially over box structure. Since the horizontal tail is removable, the glass applied outside (fore and aft) the box may have little or no anchor to carry loads to, and will be ignored.

So, a fabric width of 17.5 inches at an average distance of (5 + 4.25) / 2 = 4.625, inches, the moment produce by the fabric, at failure time for the okoume element, a single layer of #7781 glass provides an additional moment of

Mt = 107lbs/in * 17.5 in * 4.625 = 8660 in-lb

Mc = 57 lbs/in * 17.5 in * 4.625 = 4613 in-lb

adding about 6% to the structural strength of the horizontal stabilizer. At this train level, the glass is far from failure, but the other woods are not. While is it possible the structure can withstand slightly higher loads even after the start of wood failure, it is unlikely to be significant.

Wing Strength

Coming…

Fuselage Strength

Coming….

Conclusions

References

(1) Understanding Flight, David F. Anderson, Scott Eberhardt

(2) Aircraft Spruce and Specialties #7781 FIBERGLASS CLOTH

"8.95 oz/yd² Medium Weight Standard Industrial Cloth. 8 Harness Satin. Thread Count 57 x 54. Breaking Strength 350 x 330 lb./in. Finished Weight 8.95 oz./yd² Thickness .009 mils."

(3) Experimental Aircraft Association, "FAA's Zodiac 601/650 Aircraft Report "

http://www.eaa.org/news/2010/2010-02-25_zodiac.asp

(4) FAA **AC Advisory Circular No: (AC)** 23-19A, **AIRFRAME GUIDE FOR CERTIFICATION OF PART 23 AIRPLANES**

Appendix A More Material Properties

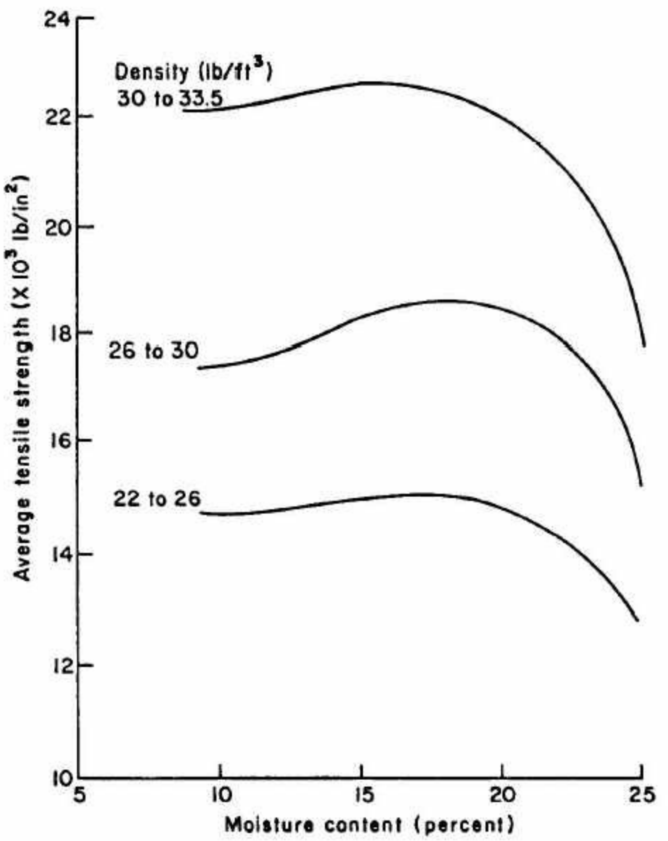


Figure 3—Average tensile strength for three density ranges of Sitka spruce at various moisture contents (Curry 1952).

Figure X Strength of Sitka Spruce by Density (USDA Forest Service FPL-RP-497)

Species	Specific Gravity	Modulus of Rupture (psi)	Modulus of Elasticity (million psi)	Tensile Strength perpendicular to grain (psi)	Compressive Strength parallel to grain (psi)	Side Hardness (pounds)
Ash (White)	.60	15,400	1.74	940	7400	1320
Balsa	.17	2,900	0.58	118	1805	100
Birch (Yellow)	.62	16,600	2.01	920	8170	1260
Cedar (Alaskan)	.44	11,100	1.42	360	6310	580
Cedar (Northern White)	.31	6,500	0.8	240	3960	320
Cedar (Port Orford)	.43	12,700	1.7	400	6250	630
Cedar (Western Red)	.32	7,500	1.11	220	4560	350
Douglas Fir (Oregon Pine)	.48	12,400	1.95	340	7240	710
Hickory	.72	20,000	2.16	?	9210	?
Lauan	.44	11,300	1.67	?	5750	590
Mahogany (Honduras)	.47 (approx)	11,600	1.51	?	6630	810
Meranti (dark red)	.45 (approx)	12,100	1.63	?	6970	630
Oak (English)	.70	9,600	1.45	?	7200	?
Oak (White)	.68	15,200	1.78	800	7440	1330
Okoume (Gaboon)	.37	7,300	1.14	?	3900	380
Pine (Loblolly)	.51	12,800	1.79	470	7130	690
Pine (Longleaf Yellow)	.59	14,500	1.98	470	8470	870
Pine (Western)	.38	9,700	1.46	?	5040	370
Pine (White)	.35	8,600	1.24	310	4800	380
Ramin	.62 (approx)	18,400	2.17	?	10,080	1300
Spruce (Black)	.40	10,300	1.53	?	5320	520
Spruce (Sitka)	.40	10,200	1.57	370	5610	510
Teak	.63	12,800	1.8	?	10,000	1030

Figure X General Wood Properties (Dudley Dix Boatbuilding)

Specifications	**Fiberglass Fabric w/System 2000/2060 Epoxy**	**Carbon Fabric w/System 2000/2060 Epoxy**	**Kevlar® Fabric w/System 2000/2060 Epoxy**
Fabric Specifications	Style 7781, 9 oz, E-Glass	5.6 oz., 3K Carbon	5 oz. Kevlar®
Laminate Construction	10 Plies Glass	10 Plies Carbon	10 Plies Kevlar®
Laminate/Resin Content	50% Resin/50% Glass	56% Carbon/44% Resin	51% Kevlar®/49% Resin
Elongation @ Break %	1.98%	0.91%	1.31%

Tensile Strength, PSI	45,870 PSI	75,640 PSI	45,400 PSI
Tensile Modulus, PSI	2,520,000 PSI	8,170,000 PSI	3,770,000 PSI
Flexural Strength, PSI	66,667 PSI	96,541 PSI	34,524 PSI
Flexural Modulus, PSI	3,050,000 PSI	6,480,000 PSI	2,500,000 PSI

Table X Glass Reinforcement Properties, (Fibre Glast Corporation)

Modulus of Rupture (www.grantadesign.com)

Units: SI: MPa; cgs: 10^7dyne/cm^2; Imperial: 10^3psi

When the material is difficult to grip (as is a ceramic), its strength can be measured in bending. The modulus of rupture (MOR) is the maximum surface stress in a bent beam at the instant of failure. One might expect this to be exactly the same as the strength measured in tension, but it is always larger (by a factor of about 1.3) because the volume subjected to this maximum stress is small, and the probability of a large flaw lying in the highly stressed region is also small. (In tension all flaws see the maximum stress.)

The MOR strictly only applies to brittle materials. For ductile materials, the MOR entry in the database is the ultimate strength.