# Laminated Bamboo Structures for a Changing World

Many subtropical locales are subject to cyclone, earthquakes and floods. Many have rapid population growth and informal settlement aggregation lacking infrastructure and building codes. They also have bamboo. Bamboo is generally known as a highly sustainable building material due to its rapid growth cycle and high rate of crop yield. Laminated Bamboo may hold the solution to the building challenges of these cities...

**Hollee Hitchcock Becker**
Catholic University of America

### BAMBOO

Bamboo is a subfamily of grass that grows in tropical, subtropical and even temperate regions receiving adequate rain. Of the roughly 1400 species of bamboo, it is the woody bamboos that are structurally of interest.

Woody bamboo species are divided into two groups: the tropical woody bamboo (Bambuseae) and the temperate woody bamboo (Arundinarieae). Bamboo species vary in height, diameter and wall thickness. Those with the best structural properties are from the genus Guadua, Dendrocalamus or Phyllostachys. Guadua is native to Central and South America, while Dendrocalamus and Phyllostachys are native to Asia.

Golden Bamboo (Phyllostachys aurea) was introduced to the United States in 1882 and is considered an invasive species while Giant Cane (Arundinaria gigantea) is a native species. Both have small diameter culms are are not considered the best choices for structural uses. However, the climate of

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Figure 1: Areas of woody bamboo growth (Clark, 2005)

Allowable Stresses (psi)

| Species | Bending Fb | Tension Ft | Shear Fv | Compression parallel to grain Fc | Modulus of Elasticity E |
|---|---|---|---|---|---|
| Raw Bamboo[1] | 3,450 | 4,070 | 313 | 1,270 | 1,560,000 - 2,070,000 |
| Douglas-Fir Larch[2] dimension lumber Select Structural | 1,500 | 1,000 | 180 | 1,700 | 1,900,000 |
| Douglas-Fir Larch[2] dimension lumber No. 2 | 900 | 575 | 180 | 1,350 | 1,600,000 |
| Douglas-Fir Larch[2] dimension lumber construction grade | 1,000 | 650 | 180 | 1,650 | 1,500,000 |
| Southern Pine[2] 2X4 Dense Select Structural | 3,050 | 1,650 | 175 | 2,250 | 1,900,000 |
| Southern Pine[2] 2X4 No. 2 | 1,500 | 825 | 175 | 1,650 | 1,600,000 |
| Southern Pine[2] 2X4 construction grade | 1,100 | 625 | 175 | 1,800 | 1,500,000 |

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the Pacific coast of California and Oregon as well as the Mid-Atlantic and Southeastern States is adequate for the propagation of structurally preferred bamboo species in the genus Guadua, Dendrocalamus and Phyllostachys.

Bamboo has been used as a structural material for centuries. Traditionally, the bamboo pole is used intact and tethered to adjacent poles to create a structure. Mechanical connections are difficult because of the hollow cylindrical shape of the bamboo pole and because of the variability of pole diameters and wall thicknesses.

Bamboo has several advantages over wood. Bamboo is a rapidly renewable material with a 3-5 year regrowth rate compared to a 20-25 year renew rate for timber. Bamboo yields measured in lbs/acre are four times that of wood (Lugt 2006). But perhaps the most significant advantage Bamboo has over timber is found in its structural properties. As shown in Figure 1, all Allowable Stresses except for Compression parallel to the grain are greater for raw bamboo than those of most wood species. This information indicates that raw bamboo poles are a good material for beams, but not necessarily for columns or other compression members such a top struts in a horizontal truss.

If bamboo is laminated to form structural components, the material properties become significantly better than those of laminated wood, as shown in Figure 2. And yet, laminated bamboo is only recently becoming a material of interest to designers.

Allowable Stresses (psi)

| Species | Bending Fb | Tension Ft | Shear Fv | Compression parallel to grain Fc | Modulus of Elasticity E |
|---|---|---|---|---|---|
| Laminated Bamboo[1] | 12,800 | 21,465 - 55,594 | 2,901 | 13,488 | 2,900,000 |
| Laminated Bamboo[2] | 16,104 | 13,764 | 1,307 | 8,659 | |
| Laminated Southern Pine 30F-E2 used primarily in bending | 2,400 | 1,350 | 300 | 1,750 | 2,100,000 |
| Laminated Southern Pine 50SPN1D14 primarily in compression | 2,300 | 1,550 | 260 | 2,300 | 1,900,000 |

sources: 1 Lamboo Inc. 2011
2 Correal 2010

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Figure 2: Comparison of Allowable Stresses in Raw Bamboo to selected dimensional lumber species and grades.

Figure 3: Comparison of Allowable Stresses in Laminated Bamboo to laminated Southern Pine.

Mahdavi (Mahdavi  2011) lists challenges to laminated bamboo construction.  Mahdavi states that "Normal precautions should be taken for moisture and dimensional stability as would be done for wood."  While this is true, laminated bamboo is more dimensionally stable than laminated wood products. (Nugroho 2001, Lamboo 2011)  A second challenge is that "Adhesives do not bond well to bamboo without adequate surface treatment."  To mitigate the bond issue, the natural wax must be chemically removed or preferably scrapped from the culms. The only challenge to this problem is one of economy.  Any additional step in the lamination process requires more labor.  Mahdavi addresses this by stating "Bamboo's cost is competitive in its natural form but significantly more expensive than alternatives in its processed form."  But the most significant challenges listed by Mahdavi are that "Construction and engineering professionals around the world are not yet adequately familiar with modern bamboo structure design" and "Formal codes and standards have not yet been developed."  There is a stigma associated with bamboo.  It is considered a construction material of the indigent.  In cities such as Dhaka, bamboo construction is shunned in favor of unreinforced masonry construction despite the seismic risks. In the United States, many designers have not been introduced to bamboo as a building material during their architecture education and are baffled by the lack of building codes in existence to direct its use.  Despite these challenges, laminated bamboo can be a practical structural solution in many design applications.

### LAMINATED BAMBOO IN AREAS OF RAPID POPULATION GROWTH

Many cities in developing nations are seeing rural-urban migration at rates beyond the capability to house.  When this occurs, informal settlements grow and the quality of life for all inhabitants decreases. The population of the Dhaka metropolitan area is 16.6 million with over over half living in informal settlements outside the city limits.  Considering that at least half of the current population of Bangladesh occupies housing at risk of flooding and that it is predicted there will be another 100 million people by 2050, 175 million people will need homes in the next forty years.  Sao Paulo, Brazil, has a seen a population increase of 33% in the past 20 years to a total of 11.4 million with 24% of its population born elsewhere.  Sao Paulo has over three million inhabitants who live in favelas.

Housing solutions are needed in over 250,000 slums around the world that house 31.6% of the world's population (Chiodelli, 2010).  With the exception of North Africa and the Persian Gulf regions, most areas of rapid population growth can support the cultivation of or have a large supply of bamboo. Therefore, it makes sense to utilize this rapidly-renewable resource. Housing solutions in areas of rapid population growth and in areas of disaster mitigation must respond to the challenges of rapid construction and delivery, economic viability and sustainable practices.  The structure must be resistant to climatic events such as cyclones and flooding, as well as seismic activity.

Modular housing is a practical solution to the challenges of housing in rapid population growth areas.  Modular units require less on-site time than building on-site.  They can be manufactured at optimum rates for each facility and delivered as needed to sites.  Because there is a controlled environment for building with lighting, rain protection and the like, modules can be assembled around the clock if necessary. Modular units can form various schematic assemblies to suit varied programmatic needs. By building several basic core module typologies, housing can be assembled in a variety of forms. The only disadvantage to prefabrication and modular design is that transportation of the modules to the site requires road infrastructure and a crane for placement. Because modules must be designed to be transported, they can serve a double purpose as a shipping container for transport of emergency supplies or additional building materials.

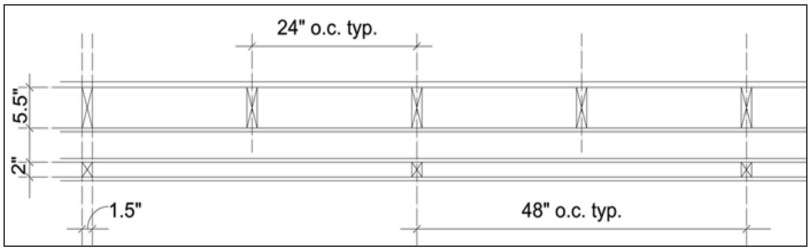
Moment frames are ideal for modular construction because openings can be placed anywhere, maximizing the flexibility of the design. Moment frames have rigid connections that resist rotation, causing the column to resist the lateral force through shear. As a result, the additional shear and moment develop in the beams and columns, must be added to gravity loads when designing the components. The loads are assumed to be resisted equally by each module column line in a given direction. Given the need for floor plan flexibility, interior column lines should use moment frames as a lateral bracing system.

The use of laminated bamboo as the primary material in the modules allows for the growth of local industries in the planting, harvesting, processing and laminating of the bamboo and also in the assembly and transportation of the modules. These industries can alleviate the housing shortages at present and provide an export commodity to nearby nations with similar housing needs in the future. Growing, harvesting and laminating bamboo can all occur in places that lack infrastructure. The lamination process involves slicing the culms, removing the natural wax coating, treating and drying the pieces, gluing the pieces together and cutting or planing to the final shape. All of the steps can be accomplished without the use of electricity by using clamps or counter-weights for applying pressure to the bamboo strips after gluing (Mahdavi 2011).

The greatest challenge to the use of laminated bamboo is cost. Rittironk (Rittironk 2009) compared costs of dimensional lumber to laminated bamboo and found that despite the fact that laminated bamboo used less material, the project cost was three times that of dimensional lumber. It should be noted, however, that the costs were calculated based on purchasing materials in Chicago. In areas with limited timber resources and low labor rates, laminated bamboo is more competitive. Still, the cost of adequate housing may be unattainable to most of the world's poor without assistance from government or philanthropic agencies.

### APPLICATIONS IN THE UNITED STATES

In the United States, western framing remains the most common residential structural type. Multi-family dwellings utilizing western framing are limited by code to 4 levels in height in most locations. A comparison of a 4-level dimensional lumber structure using Douglas Fir Larch, construction grade (DFL) to a laminated bamboo (LBL) structure of equivalent height and applied loads yields the following:



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Floor joists:
A floor joist spaced at 16″o.c. with a span of 12′ and supporting a uniform load of 80psf require a 2X10 DFL (1.5″ X 9.25″) compared to a 1.5″ X 6.5″ LBL. Although a mere 2.75″ in LBL depth is required for bending, a limitation of L/240 for deflection requires a 6.5″ depth.

Stud walls:
An 8′ stud wall supporting 1920#/f and given adequate sheathing requires either 2X4 DFL @ 16″ o.c. or 2X6 DFL @ 24″ o.c. The same wall could be constructed of LBL using 1.5″ X2″ studs @ 48″ o.c. The drawback of the LBL configuration is that the limited cavity space reduces the amount of insulation that can be placed inside the wall and requires a rethinking of electrical and plumbing systems. Further there are limitations to height based on the slenderness requirement of $L_e/d \leqslant 50$. The conclusion is that while LBL affords less material and lighter construction, it doesn't necessarily make sense to use LBL in western framing.

Where LBL does make sense is in post and beam construction. For beams where deflection governs, given identical cross sections and spans, and LBL beam can carry 1.93 times the load of a DFL beam (ELBL/EDFL = 2,900,000/1,500,000 = 1.93). But in short, heavily loaded beams where flexure governs, given identical cross sections and spans, and LBL beam can carry 1.93 times the load of a DFL beam (FbLBL/FbDFL = 12,800/1,987= 1.93).

A more significant comparison can be made using a typical office building floor plan. Beams spaced 48″ o.c. with a span of 24′ and supporting a factored load of 140psf require a 4″ X15.5″ LBL compared to a 6X20 DFL (5.5″ X 19″) or a 4X18LVL. Given identical decking, in a 24′ X 24′ bay, the difference in the size of the beams amounts to 35.4 cubic feet of material and a weight difference of .55k/bay compared to DFL and .35k/bay compared to LVL. On its own, this is not significant enough to justify the added expense of laminated bamboo.

| ALLOWABLE LOADS (KIPS) | | | | | |
|---|---|---|---|---|---|
| ACTUAL COLUMN SIZE | LBL | DFL | LBL/DFL RATIO | LVL | LBL/LVL RATIO |
| 5.5" X 5.5" X 12' | 55.1 | 23.8 | 2.32 | 53.4 | 1.03 |
| 7.25" X 7.25" X 12' | 161.9 | 66.6 | 2.43 | 107.8 | 1.50 |
| 9.25" X 9.25" X 12' | 409.3 | 153.1 | 2.67 | 249.7 | 1.64 |
| 11.25" X 11.25" X 12' | 834.1 | 274.2 | 3.04 | 450.7 | 1.85 |
| 13.25" X 13.25" X 12' | 1,450.8 | 420.2 | 3.45 | 694.6 | 2.09 |
| 15" X 15" X 12' | 2,129.9 | 566.0 | 3.76 | 937.8 | 2.27 |
| 17" X 17" X 12' | 3,032.2 | 752.4 | 4.03 | 1,248.8 | 2.43 |
| 19" X 19" X 12' | 4,045.5 | 960.5 | 4.21 | 1,596.0 | 2.53 |

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Figure 4: Stud wall horizontal section comparing DFL construction (top) to LBL construction (bottom).

Figure 5: Comparison of Allowable Loads on LBL to DFL and LVL columns.

A comparable steel beam would be a W12X19 with only .11k per bay additional weight. The only advantages laminated bamboo has over steel are the fact that bamboo is a rapidly renewable resource and the fact that the embodied energy in the lamination of bamboo is only 33% that of steel and 85% that of LVL (Lamboo2011).

LBL columns make even more sense. Comparison of DFL to LBL columns reveals that when given identical unbraced lengths and end conditions, and following AWC guidelines for Cp, LBL columns can carry between two and four times the load of DFL equivalents. It should be noted that columns will have the same size when the loads are so small as to use the minimum dimensions, Le/d.

### LAMINATED BAMBOO APPLICATION IN HIGH-RISE STRUCTURES

Given that laminated bamboo columns and walls can support two to three times more weight than timber equivalents, it is logical to explore LBL as a material for high-rise structures. There has been research and development in the design of wood high-rise structures in the past few years. Life-cycle Tower in Bregenz, Austria, designed by Hermann Kaufmann is an example of efforts that utilize mass timber and prefabrication. Michael Green Architecture in Vancouver is also exploring Mass Timber. Mass Timber is a term that applies to Cross-laminated timber (CLT), Glue-laminated Timber (GLULAM) and Structural-Composite Lumber (SCL) which includes Laminated Veneer Lumber (LVL) and Oriented Strand Board (OSB). Given that LBL has higher allowable stresses, it makes sense to explore the possibility of LBL high-rise structures.

As an example, consider a 30 level commercial high-rise with a 24′ o.c. orthogonal square column grid. Given a factored load of wu = 1.6(80psf live load) + 1.2(60psf dead load) = 200psf, and a tributary area of 576sf based on columns spaced at 24′ o.c., the load per level on an interior column would be P = 200psf(576sf)/1000#/f = 115.2k per level. Assuming a floor to floor height of 12′, and lateral loads resisted by shear walls, a 30-level high-rise is possible using laminated bamboo lumber. Columns would have a 30(115.2k) = 3456k load on the bottom segment and would need to be 18″ square at the base, but could be tapered or stepped down on higher levels.

The shear walls have a 12ft segment height, 24′ width (between columns), and a wall thickness of 8″. Based on wind loads of 150mph speeds and a tributary width of 36′, an additional compressive load of 167.88k must be added to the bottom segment, requiring adjacent columns to increase in size to 18.25″ square. The size is adequate for shear.

If the building structure is a braced frame with two diagonal braces per line and again with a tributary width of 36′, the additional load on the column under the most compression from 150mph wind loads would be 144.72k. The total axial load at the bottom leg of the column would be 3456k + 115k = 3571k indicating that the column would need to be 18.25″ square in cross-section at the base.

If the building structure is a moment frame with a tributary width of 24′ and 5 columns per line, the additional moment would be 694.7k-f in an interior column and 347.4k-f in an exterior column. The additional axial load in an exterior column would be would be 951.2k. The columns would have an increased axial load of 3456 + 951 = 4407k plus the 347.4 k-f moment requiring an increase in cross-section from 6″ square at the top to 21.5″ square at the base for a moment frame. In a comparable steel moment frame of the same configuration as the example above, the column would vary from a W14X22 at the top to a W14X455 at the base of the column.

Structure weight: 72′X120′X30level high-rise with 24′X24′ bays, and beams at 4′o.c.

LBL: 3390 – 4″X16″X24′ beams @ 1519k + 24 – columns @ 642k = 2161k

STEEL: 3390 – W12X19beams @ 1546k + 24 – columns @ 1953k = 3499k

The LBL moment frame weighs only 62% of the steel moment frame and has only 20% of the embodied energy in the material processing.

### THE CHALLENGES TO LBL CONSTRUCTION IN THE UNITED STATES

Structurally and environmentally, LBL makes sense on large-scale construction. The barriers to use include lack of recognition by building codes and cost. At 702$/ton, the initial material cost of beam and column steel would be just over $1.1 million compared to an average FOB US LBL cost (Alibaba 2013) at 2539$/m3 = 70$/f3 which would cost over $3.3 million. The problem with this comparison is that LBL beams today are in limited use. Manufacturers of LBL do not have the economy of scale to reduce prices. From an initial cost perspective, Laminated Bamboo Lumber will become more competitive with steel if demand for LBL structures rise. In the United States, the cost of LBL could be reduced by using locally grown bamboo. Most LBL manufactured in the United States uses bamboo grown in Central and South America. A life Cycle assessment of laminated bamboo purchased from China, but manufactured in the Netherlands (Lugt 2012) shows that 29.6% of the carbon footprint and 54.8% of the ecocosts (cradle to gate) are generated by transportation. The Southeastern United States has a humid subtropical climate ideal for growing bamboo. If bamboo were propagated and processed on former tobacco fields, transportation factors of LBL would be eliminated. This would have the added benefit of phasing out tobacco without destroying the livelihood of farmers.

ASTM 11a 5456 – Laminated Veneer Bamboo is a new addition to the ASTM standards for evaluating structural composite lumber products. This is the first step in true codification of LBL. As a recognized material, LBL can be easily specified for use. This milestone indicates that acceptance and recognition of LBL as a structural material is growing in the design community.

### EDUCATION

The big three: concrete, steel and wood have been the mainstay of structural education for architecture students, as well they should be since virtually every building relies on one of these materials. But, the importance of educating architects and especially architecture students about alternative structural materials is important in an age filled with sustainable challenges. Just as a course in steel design should include other metals such as titanium, courses in wood design should include laminated bamboo when discussing glu-lams. A

Structural Systems course should include evaluations of structural materials based not only on allowable stresses, but on environmental impact as well. If students are educated in the benefits and pitfalls of alternate structural materials, they may become motivated to research and use these materials in studio, thesis and future professional designs.


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