For the Hannover World Exposition next year, the 9,000 square foot (836.1 m^2) NGO pavillion has been built by Simon Velez, and many more people will see what is possible with bamboo construction.

As an architect practicing in the western U.S., I've been intrigued by the structural qualities of certain bamboos. I am working to find practical means to introduce the use of these bamboos into U.S. building practices and to explore other structural uses of bamboo.

Bamboo has been documented as having over 1,500 different uses. In the area of building, these include uses in fences, gates, trellises and every part of buildings. Bamboo tools, utensils and buildings are an important part of life for half the world's population. In temperate climates around the world, bamboo fills the need for building materials whose supply can be maintained indefinitely with little residual damage.

The construction of bamboo structures has been traced back to 3500 B.C. It can last for several hundred years, as evidenced by the rafters of some traditional Japanese farmhouses. Bamboo structures were popular in Central and South America among both rich and poor until several catastrophic fires in larger Colombian cities around the turn of the century relegated the use of bamboo to the poor. It is estimated that over 800,000 people live in bamboo structures in Guayaquil, Ecuador, today.

What is most important is the establishment of a production system; gaining access to inexpensive land that is not usable for any other purpose, choosing appropriate species, allowing time for maturity, understanding the aesthetics of working with cylindrical materials in a predominantly rectilinear society, learning to distinguish exceptional working stock, and developing a design approach that takes full advantage of both the strength and beauty of the timber bamboo—these are our challenges.

BAMBOO AND SUSTAINABILITY

Bamboo meets the following basic criteria for a sustainable building material by being:

- **Renewable.** The Phyllostachys varieties—those most suitable for growing and building in the U.S., where

The views expressed here are those of the author and do not necessarily reflect the opinion or agreement of the International Conference of Building Officials.

ding With Bamboo

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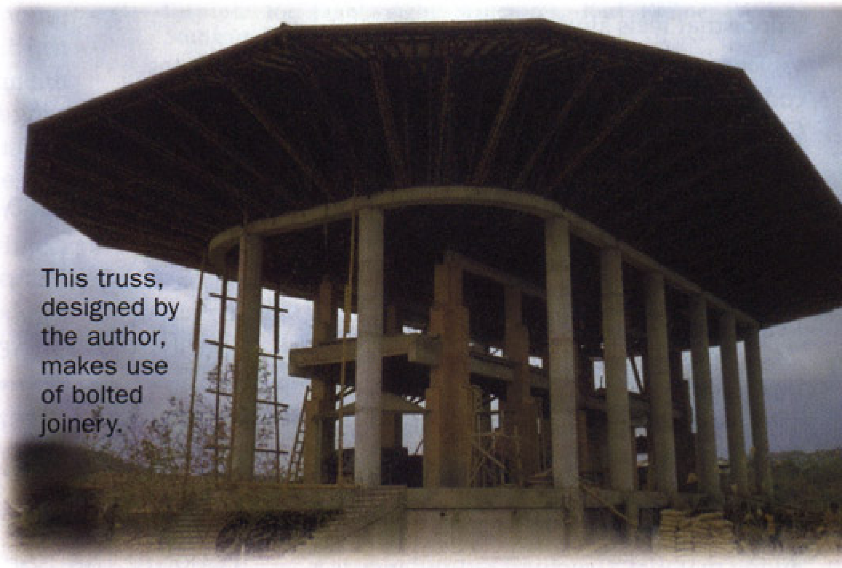

This truss, designed by the author, makes use of bolted joinery.

we must deal with frost—will grow 10 to 12 inches (254 mm to 305 mm) a day once a grove is established. The record is 49 inches (1245 mm) in a day. Culms (the living poles) achieve all of their growth in an initial six-week spurt, then spend the next three years replacing sugars and water with silica and cellulose. Structurally, they are only useful after that third year, which is about when the plant considers the culm expendable.

- **Plentiful.** Our current meager U.S. supply of timber-quality bamboo could increase manifold within a decade with species selection appropriate to the microclimate and water and nutrient availability. For now, strong tropical varieties are being imported from Asia and South America, along with temperate varieties such as Moso, and can be of great help in getting the industry started here.
- **Local.** Bamboo concentrates a large amount of fiber in a small land area, creating a rare situation in which a single person can be both the producer and consumer of a building material.
- **Waste-reducing.** As is nature's general practice, nothing goes to waste. The leaves are a more nutritious animal feed than alfalfa, and bamboo compost serves to fertilize the next generation.

ATTRACTIVE ATTRIBUTES OF BAMBOO PRODUCTION

Bamboo production systems in Japan, Southeast Asia, and Central and South America, requiring only minimal infrastructure and equipment, allow a small number of people to carry out the process from planting through utilization. Every part of the plant has a use, and harvesting for that use at the appropriate time not only doesn't hurt the plant but encourages future vigor. Groves can be located to take advantage of the plant's unusual ability to quickly process water and nutrients left over from livestock farms, sewage treatment plants and industrial processes. In contrast to most plants, the addition of fertilizer does not diminish the quality of bamboo poles, as there is a time lag during which the energy is stored in the rhizome for later release in the formation of the next year's culms (Liese '92). Meanwhile, those rhizomes are useful for securing topsoil and for erosion control. The plants use transpiration to create their own microclimate, cooling a grove (or a house located in a grove) as much as 10°F to 15°F (6°C to 8°C). The branches and leaves are useful as animal fodder, containing a higher protein content than alfalfa.

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STRUCTURAL PROPERTIES

Bamboo is an extremely strong fiber, with twice the compressive strength of concrete and roughly the same strength-to-weight ratio of steel in tension. In addition, testing has shown that the shape of bamboo's hollow tube gives it a strength factor of 1.9 over an equivalent solid pole (Janssen '97). The reason being that, in a beam, the only fibers doing the work are those in the very top (compression) and bottom (tension). The rest of the mass is dead weight.

The strongest bamboo fibers have a greater shear resistance than structural woods, and they take much longer to come to ultimate failure. The ability of bamboo to bend without breaking may make it unsuitable for building floor structures in this country because of its natural bounciness. There seems to be a very low tolerance for deflection in the U.S. so few are likely to accept a floor that feels alive.

Through most of the world, there is no provision in the codes for bamboo construction. Successful experiments, by Colombian architect Simon Velez, to achieve 66-foot (20 354 mm) spans and 30-foot (9144 mm) cantilevers were conducted in an area not requiring inspection of structures. Now that these exist, they stand as proof of what works and as models for future designs. Even one-quarter of Velez's spans would be adequate for most of our needs. Because of the relative scarcity of timber bamboo in the U.S., one of the best uses for this giant grass is as a truss, thereby taking advantage of both its strength and its beauty.

Bamboo is a strong fiber, with twice the compressive strength of concrete and roughly the same strength-to-weight ratio of steel in tension.

Although bamboo is a bending and forgiving material, structural redundancy is a must in truss design. It is imperative that we overbuild; a structural failure at such an early stage would be catastrophic. It is crucial to understand which members are in tension or compression, and which points in a structure experience maximum shear and moment. Ambitious designers should do some small-scale work with the material to get an idea of what feels right, then find a structural engineer who can do the calculations for them.

EARTHQUAKES AND WIND

There are two strategies for overcoming lateral forces in a bamboo structure. The first, represented by more recently engineered Latin American structures, relies on the shear resistance provided by mortar on both the bamboo-lathed walls and the roof. The success of this approach was demonstrated in April, 1991, when 20 houses constructed in Costa Rica for the National Bamboo Foundation survived a 7.5 earthquake. The second approach takes advantage of the forgiveness of the traditional lashed, pinned or bolted joints found in both Asia and the Americas. In the Colombian earthquake in January, 1999, nearly all of the 500 people killed were hit by falling concrete. The bamboo structures survived uniformly unscathed, including this tower with a bamboo root structure located within a few thousand meters of the epicenter. Even structures created with intuitive engineering and nonoptimized joinery take great advantage of the broad elastic range of bamboo, allowing it to be pushed out of shape and then returned once the load is removed. It is difficult to cause failure of bamboo in pure compression or tension and elastic bending can be quite dramatic and still not result in failure. What is truly critical is that place where forces are concentrated—the joints.

JOINERY DESIGN

Simple, quick joinery systems based on pegging and tying have evolved to take advantage of the strong outside fibers of the hollow bamboo tube. More recent systems have been engineered to make joinery stronger and less labor-intensive. Lashed joinery has been used successfully for millennia. It allows for movement, and if natural fibers such as jute, hemp, rattan or split bamboo are used while still green, they will tend to tighten around the joint. Unfortunately, the seasonal moisture changes in most of the U.S. will cause bamboo to expand and contract by as much as 6 percent across its diameter (Dunkelberg '85), causing a slackening of the joint, and not all joints may remain accessible for tightening.

The joint of preference has become the one developed by Simon Velez in Colombia. He relies on a bolted connection, but with an understanding that the bolt alone concentrates too much force on the wall of the bamboo. Therefore, the void between the solid internal nodes is filled with a solidifying mortar. Where members of a truss come together at angles and tension forces are anticipated, a steel strap is placed to bridge the pieces—mostly because the configuration of the strap allows that connection. Nevertheless, with regard to the dozens of structures he has built, Velez claims, "I have never seen the bamboo fail, only the steel straps have failed under load testing" (Velez, '96).

CHECKLIST FOR A WELL-DESIGNED BAMBOO TRUSS STRUCTURE

- Good, solid static analysis to ensure that loads are distributed evenly among the joints and axially along the pole.

- Slenderness ratio of less than 50 (Arce '93).
- Bolted joints with solid-filled internodes.
- Dry poles that are still easily workable—about six weeks after harvest is ideal.
- Harvest when sugar content in the culm is low.
- Keep the poles out of the sun and dry.
- Find a way to obtain lateral strength. Either create a shear panel consisting of a mortar-bed over lath, or avoid mortar altogether and allow the structure to deflect and return.
- Refer to the engineering formulas and testing criteria developed by Jules Janssen (Janssen '97).

CODE APPROVAL

Jeffree Trudeau and David Sands of Bamboo Technologies in Hawaii, have been working to achieve code acceptance by first building a ferrocement house with stay-in-place formwork panels and joists that just happened to be bamboo. They are currently working with ICBO Evaluation Service, Inc., and Kurt Stochlia to prepare both the acceptance criteria as well as an evaluation report to provide future guidelines and reference. An interim option is provided in another jurisdiction that requires the stamp of a structural engineer or architect and special inspection [*Uniform Building Code*™ Section 306.a.14]. They also suggested that a prescriptive code be developed by the local design community to "provide uniformity in submittals."

THE CHALLENGE

While there are already a few thousand timber bamboo growing in the western and southern U.S., a complete system of growing, processing and, especially, using bamboo as a building material does not yet exist in this country. Bamboo structures can make a significant contribution to local self-reliance, allowing affordable construction without dependence on highly industrialized, proprietary systems, while taking some of the pressure off of the forests. ■

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