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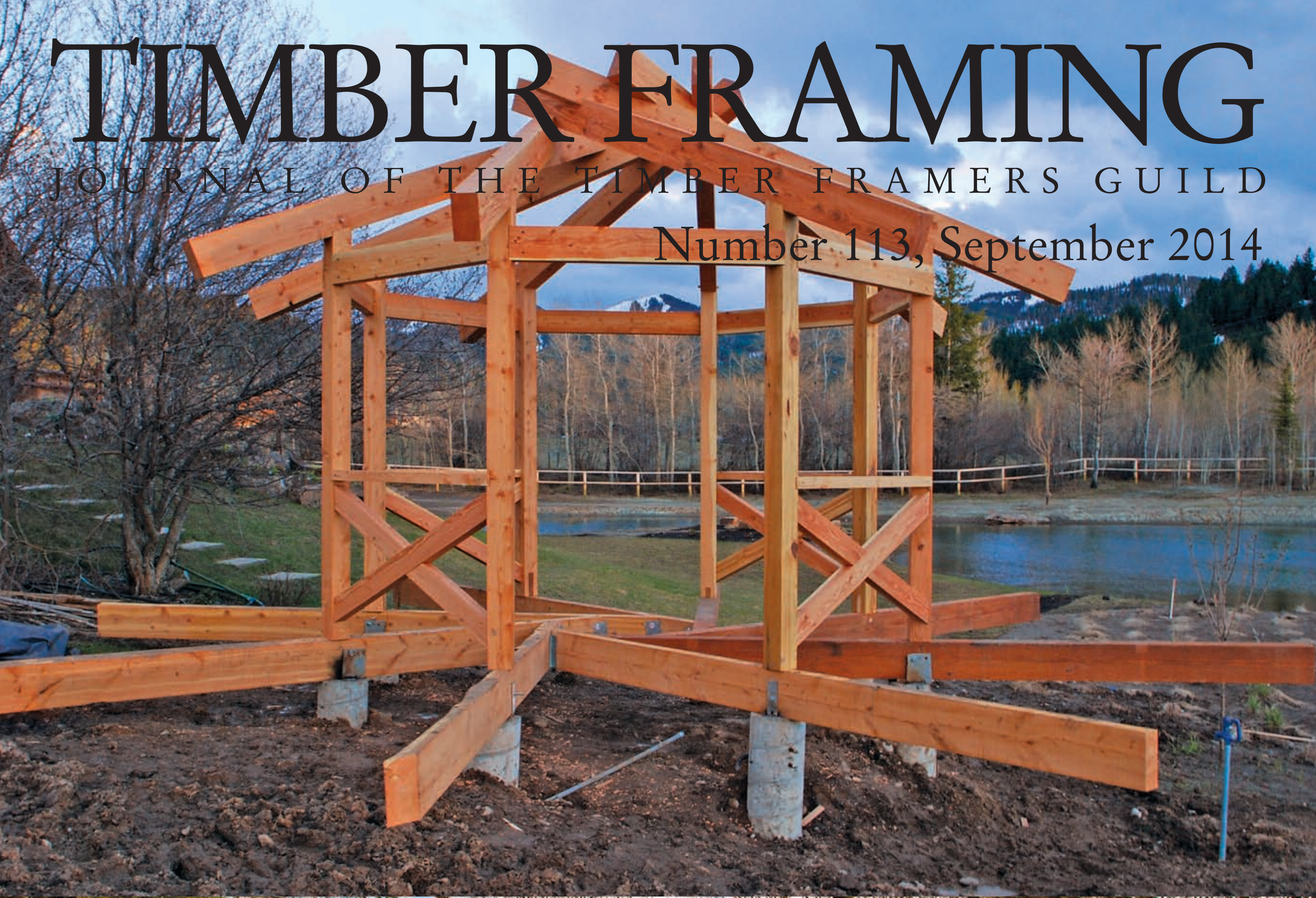

Reciprocal Frame Gazebos

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On the front cover, reciprocal-framed gazebos in Idaho (upper photo, by Adam Riley) and Vermont (lower photo, by Daniel Girard). On the back cover, the Mathematical Bridge at Queens' College, Cambridge, England, a 1748 design rebuilt once and still in daily service, seen during a summer rain. Photo by Philip S. C. Caston.

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TIMBER FRAMING, Journal of the Timber Framers Guild, appears in March, June, September and December. The journal is written by its readers and pays for interesting articles by experienced and novice writers alike.

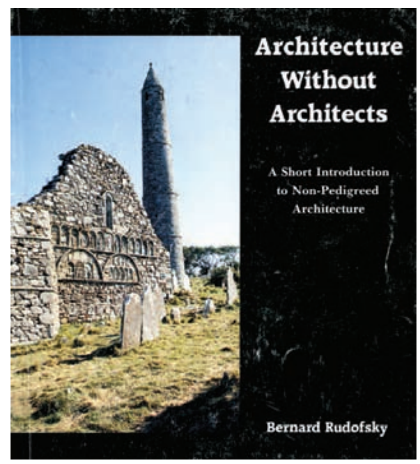
1985

BOOKS

Architecture of Place

Architecture Without Architects: A Short Introduction to Non-Pedigreed Architecture, by Bernard Rudofsky. New York, Museum of Modern Art and Doubleday, 1964. 8½ x 9½ in., 140 pp., 156 illustrations. Reprinted 1987 by the University of New Mexico Press. ISBN 978-0826310040, 157 pages, softcover, $24.95. A digital copy of the book is available at Monoskop.org.

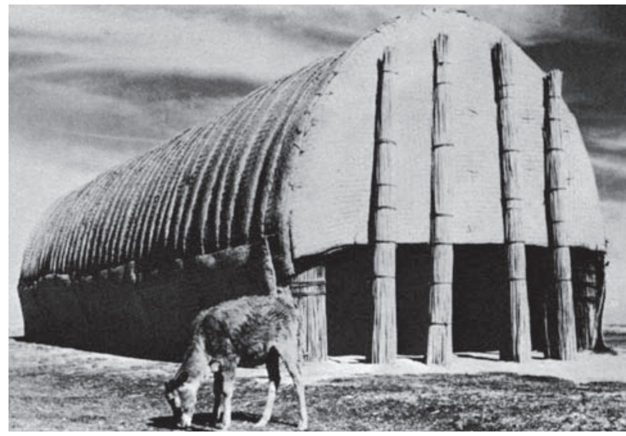
THE photograph on the facing page at top left depicts moving day in Guinea, a cultural phenomenon that represents a characteristic attitude toward architecture. Unlike in the Western world, among some African and Asian populations it's unacceptable to move family from one household to another, utilizing space that somebody else occupied before and leaving the old dwelling to others. The reuse of a private place even may be considered humiliating. Thus, when nomadic people of Guinea change location, they take the house with them, bearing the roof on their heads. The household and its owners become a single organism. The image of this walking construction embodies the emotional attachment of the human to the house, a fundamental principle of respectful care for the hearth and protection of the intimacy it provides. The necessity of shelter is related to the pursuit of privacy, the development of the community, the tendency to define enclosed spaces and, ultimately, the need to build.



This structure is one of the examples that Bernard Rudofsky (1905–1988) describes in his book *Architecture Without Architects* (1964), a catalogue of the exhibition that took place 50 years ago at the Museum of Modern Art in New York and presented results of Rudofsky's study of vernacular architecture, a collection of astonishing buildings of all kinds from various parts of the world. (The cover image shows Ardmore Round Tower, County Waterford, Ireland, possibly 12th century.) The evidently subjective selection is meticulously composed and successfully describes the common need to generate useful structures, not necessarily sophisticated designs. This book remains one of the leading publications on what Rudofsky calls non-pedigreed architecture, even though most likely the latter is still situated in a somewhat obscure niche among architectural environments. Rudofsky's work is not so widely recognized as it might be, perhaps because it was published in a historical moment when academics were still strongly attached to the philosophy of modernism, searching for

Collection Musée de l'Homme

Gavin Maxwell



industrialized solutions, focusing on innovative forms and often abandoning the indigenous.

Bernard Rudofsky was of a nomad spirit himself. Born in Moravia (now the Czech Republic) in 1905, he studied architecture in Austria and later worked in Germany, Spain, Italy, Denmark, Japan, Brazil and the United States (not to mention the travels he did for his research). A great mind and a man of many talents, among his occupations we can name clothing and furniture designer, curator, photographer, university professor (MIT and Yale in the US, Waseda in Japan, the Royal Academy of Fine Arts in Denmark) and, of course, architect. He was also the author of *Streets for People: A Primer for Americans* (1969), in which travel was one of the essential components of his attitude—he would treat "life as travel" and "travel as a lifestyle." His paths were naturally defined by the architectural examples he found worth taking a closer look at.

Architecture Without Architects carries a certain narrative within, if not a literary one. There is not much text in the book, only brief (if dense and witty) legends to explain the extraordinary photographs that already tell their own story. In a lengthy illustrated preface, Rudofsky explains the idea of vernacular architecture not as a regulated discipline of design, but as an act that fulfills the instincts to provide a roof over one's head, define boundaries of a community or explore the realm of what is beyond the human scale. He proposes that "the philosophy and know-how of the anonymous builders present the largest untapped source of architectural inspiration for industrial man."

The main body of the work begins with illustrations of large-scale land interventions. Even though most of them are horizontal formations and don't include any bearing structures, they are definitely enactments of architecture as artifacts to the landscape.

Rudofsky smoothly guides the reader through cases of human-reshaped sections of nature and consciously chosen living sites, toward samples of settlements that preview the idea of urban planning. Further sections show the variety of solutions people come up with, according to the accessible materials and characteristics of the natural conditions they encounter. Most buildings depicted represent unusual invention, courage and aesthetic awareness, such as the Iraqi reed (*Phragmites communis*) building shown framed above and sheathed above right. The whole story is closed by impressive examples of virtuosity and complex structures based on builders' skills and fantasies.

One of the things I appreciate in this catalogue is the fact that not even a hint of the idea of centralized progress appears, nor any suggestion of preference among particular civilizations. There is no imposed historical order or unexpressed cultural domination. All the projects mentioned in the book are equal and treated as manifestations of the vernacular genius. Italian lemon gardens are placed right next to New Guinean tree houses. The ability to build more sophisticated structures is explained as variable, determined by either the favorable environmental conditions or socially generated context (sacred or communal festive spaces, for example, are usually more decorative, bigger or wealthier).

A significant aspect of vernacular architecture is tradition. As a vessel for cultural values, tradition may be recognized as a dominating authority, but a more creative perspective perceives it as a dynamic construct that includes variations. Simon J. Bronner, in his essay "Building tradition: control and authority in vernacular architecture" (in *Vernacular Architecture in the 21st Century*, ed. Marcel Vellinga and Lindsay Asquith, 2005), remarks that tradition "demands attention to form, fidelity to cultural continuity, while inviting alteration and extension for social needs" and at the same time it is a "framework allowing for choice of adaptation." As the vernacular expresses a particular region, it carries solutions that are already verified by time and society: "Ways of living and ways of building are culturally inherited." This attitude places tradition in a substantial position in contemporary architecture and permits us to reflect more on the structures we raise today.

Vernacular architecture is an expression of the folk, popular, informal, and at the same time a set of confirmed solutions and fixed ideas. The individual designer is not the key figure here, but rather the group effort. Later the public responds to the built structure and time consumes the object, verifying its reliability. Building is a process in which the designer's idea provides only the initial impulse. The nature of the material employed as well as the skills that builders possess and the attitude they represent carry forward the process. The ultimate factor is the person or the community who uses the building.

Architectural form is of a larger scale than an object that fulfills individual ambitions only. It is an important lesson from the past, reminding us that life shapes architecture and the people who live with it. Dwelling is to be designed as a part of a greater whole, rooted in the local culture and the legacy sustained by the builders. Observation of the environment (both wild and man-made), analysis of context, and emphasis on human needs increase the chances of creating a place that will be successfully inhabited. Bronner's statement on traditions of building exposes a simple truth in a very clear way: "What is significant in the modern concept of tradition is that the past becomes part of the present as a guide to the future action."

Here are Rudofsky's comments on pictures of Phira, a town on the Greek island of Thera in the Cyclades archipelago. It is a spectacular site, elevated 660 ft. over the sea on a steep, rocky coast, situated right on the edge of a volcanic crater, repeatedly ravaged by earthquakes, yet never abandoned.

> Man's physical freedom manifests itself no doubt in his ability to choose the place on earth where he wants to live. Whereas immature reflection tends to judge by usefulness alone, a discriminating mind may ask its share of beauty. Neither privations nor danger will deter man selecting a spot that provides him with the exhilaration generated by a superb landscape.

Rudofsky's explanation of this case describes pretty well the poetry of building: the fantasy that allows people to forget about pure pragmatism and concentrate on intangible values of creating

Photos Marcos Corrales

living structures. People share the inner need to find a place where they feel safe, whether alone or accompanied. Building redefines the landscape around us and adds new perspective to our position. There is more to raising structures than the prose of life. It's also about the search for the Beautiful Place to be in and to integrate with.

Although not many of Bernard Rudofsky's house designs were built, the few that exist are scattered over the globe: Italy, Spain, Brazil, the US. When working on a dwelling, he would think of it as a kind of a paradise (for himself or for another owner), usually located on the sea, designed carefully as a harmonious composition of rectangular volumes and open levels. Modest in form, generous in space and incorporated into their natural surrounding, Rudofsky's houses are contemporary and traditional at the same time: the ambience is original but one can sense the wisdom of vernacular experience as the solid background. For himself, he selected a spot in Frigiliana, in the Spanish province of Málaga. His house (details above and below) is a culmination of lifelong study. La Casa, as Bernard and Berta Rudofsky called it, is a sensible combination of the characteristic style of the Andalusian coastal region with the designer's and his wife's understanding of the aesthetics of modern architecture. Local materials were used for the construction (*teja curva tipo árabe*, or single-curve Arabic, roof tiles; natural clay for the walls), and the shape of the house was adjusted not only to the terrain but also to trees growing on the property. Rooted in regional tradition, Rudofsky's design for La Casa is definitely an interpretation rather than a repetition of architectural specifics he encountered in this land. —Olga Micińska

Olga Micińska (olga.micinska@gmail.com), a woodworker and sculptor, travels between studios in Warsaw and the Hudson Valley of New York and has been associated with the Guild since the 2011 Gwozdziec Synagogue project.

IN MEMORIAM: Ed Levin

[Ed Levin, a Guild founder, died suddenly aged 66 in August 2013. His family endowed a Guild conference memorial lecture series in his name. At the 2014 conference last month in Manchester, N.H., Ed's son-in-law Kevin Jacoby introduced the inaugural speaker of the series, Ken Burns, coproducer of The Civil War *(1990) and other historical films, with this memoir. —Editor.]*

ON a cold Boston morning in November of 1830, Ralph Waldo Emerson sat down to his journal and wrote: "A man is known by the books he reads, by the company he keeps, by the praise he gives, by his dress, by his tastes, by his distastes, by the stories he tells, by his gait, by the notion of his eye, by the look of his house, of his chamber; for nothing on earth is solitary but every thing hath affinities infinite."

It is in this spirit that I'd like to describe a kind and wonderful man by the company he kept, the stories he told, and the ideals he cherished. For those of you who knew Ed—really knew him—you may find yourself smiling inwardly at the memory of his antics and idiosyncrasies. Perhaps you'll recall the incalcitrance of his youth with a roll of your eyes and a shake of your head. Or maybe, like me, it's a gentle malaise you'll feel, for a world prematurely deprived of a great man's contagious exuberance for food and drink and art and nature. For those of you who knew Ed Levin only by reputation, perhaps the tale of an artist so wholly in love with his medium, so dedicated to his craft, will bring you some small measure of inspiration. Regardless of whether you knew Ed well, or not at all, you may be pleased to know that my purpose here is not to proffer sainthood, whitewash difficult times, or paint anything less than the truest, most faithful picture I can manage.

My intent, rather, is to depict the character of a man who was buoyed by his passions and beset by his foibles, who lived by an insatiable desire for learning, experiencing, and enjoying. Ed's first wife, Anita, once described to me a scene from his early days as a timber framer. There she was, alone in a field, save for Ed, a small tent they called home, and the angular skeleton of a timber frame in the making. Anita, young and slight and pregnant with their daughter Cora, put a hand to her brow against the high New Hampshire sun and looked up. Her gaze floated to the treetops, scraped the cloudless sky, and settled peacefully down to Ed, perched on the far-reaching beam that held his rapt attention to the exclusion of all else.

"He worked alone," she told me. "And though it was impossible, you could just see him trying to figure out how to be at both ends of that beam at once." Of course, to Ed, the task was never impossible. These were the puzzles he lived for, the ones that started as a notion on a single sheet of paper, and then somehow became the elegant curves of a vaulted ceiling, or the hallowed halls of a synagogue.

As his career progressed, Ed found himself in fields around the world, among those who shared his passion for the long and storied tradition of timber frame design. But it was in helping his cherished community of artisans knock down their own creative barriers that Ed found his greatest passion. "He was," as friend and colleague Ken Rower said, "a timber framer's timber framer. He's the only person I know," Ken told me, "who had the complete respect of the Timber Frame Engineering Council, and never took an engineering course in his life."

Each call was an adventure, each challenge a hit of his favorite drug. And as he hung up the phone, project in hand, he'd slip sublimely from the taunting of life's shouts and murmurs; lapsing, untroubled, into the familiar embrace of quiet concentration. I can't help but smile at the thought of my old friend, hunched over the keyboard, his face pallid in the artificial computer blue. Quiet, alone, and satisfied completely in his distance from life's comings and goings, consumed entirely by the task at hand. How comforting that sounds.

In preparing to speak here today, I had the opportunity to connect with some of those who knew Ed best. I was looking for some insight, something more than I was able to divine from the too few hours I spent in his company. The danger, of course, was coming back from these conversations with too many peaks and not enough valleys, such that it might seem as if I had invented a Hollywood superhero with no faults at all. But it seems that those who loved him most, loved every aspect equally. Which, I suppose, is why they felt no compunction in describing to me both his highest highs and lowest lows, knowing full well—if you'll excuse the cliché—that the whole of Ed was far greater than the sum of his parts. With that said, I can tell you that the angular joints of his character sometimes made living, loving and working with Ed a frustrating experience indeed.

Orson Welles once said: "Everything about me is a contradiction, and so is everything about everybody else. We are made out of oppositions; we live between two poles. There's a philistine and an aesthete in all of us, and a murderer and a saint. You don't reconcile the poles. You just recognize them." I think Ed recognized the contradictions of his character. I think he wore them day in and day out, like a tattered coat, too threadbare to insulate, too familiar to replace. And even though his passion for logic, and reason, and the immutable laws of physics defined him as much as anything else, still he was beset by the inner demons that pulled his focus from the fundamentals of family, and business, and health.

In a letter to his dear friend, Dan Daley, Ed very elegantly described the warring factions of his complicated mind. "Happy Ed Levin puts in the occasional appearance, swapping out for his alter ego," he wrote. "Our dialogue got me thinking about how to frame the dichotomy between these two. Posed one way, the question is, which of these guys holds the lease and which the sublet? . . . Alternately, is unhappiness a chronic and happiness an acute condition? (One would prefer the reverse.) . . . The problem is, after decades of consideration, I don't know and am clueless how to proceed. Perhaps there is an uncertainty principle which obscures the metaphysics of happiness, since the primary observer, perpetually trapped in one state or the other, is unable to self-observe with dispassion and clarity."

I sometimes wonder if, in another time and place, Ed might have lived a life of perfect balance and equanimity. But then again, how often do we celebrate life's great thinkers and doers for their sameness, their convention, their mild temperament? Who could honestly wish for Ed to have been plain and predictable, when so many of us found pleasure in his messy, beautiful life? Not I.

June 1st of this year was just another Sunday, unremarkable to me in every way. That is, until I realized the day marked exactly one year since the last time I had had the pleasure of Ed's company. He had boarded a train that delivered him to New York City midmorning. Cora and I met him on the corner of East 2nd and Avenue B, and steered him toward one of our favorite brunch spots to begin the day's culinary adventure. A couple of orders of fried catfish and a few too many Mimosas later, we ambled back to our apartment to escape the heat and plan our next move. I was sitting quietly, lost in my thoughts, when suddenly I looked up and chanced to see love. It was the sight of Ed and his daughter that caught my eye, as the patter of their conversation gently bent and curved. For reasons I still don't quite understand, it is the memory of that very moment, viewed with a clarity only time can provide, that illuminated for me his most precious quality: Ed was a hopeless romantic. There was romance in the stories he told. There was romance in his giddy anticipation of the Timber Framers Guild meeting he'd attend in a few short weeks. And there was romance in his delight of life's simplest pleasures, like time spent with those who require no more of us than the comfort of our company.

And now, suddenly, it's clear to me: there was a subtle romance to everything Ed did. It was the glorious frames he raised like a child; the nobility he imbued in every arch, every angle. Ed's greatest gift was his ability to infuse any structure, any story, any phrase with gravitas, whether a lonely covered bridge, quietly aging by a country meadow, or the nostalgia of a long ago summer day, as in another letter to a dear friend. "What I have savored down the years," he wrote, "is the delicious irony that, freshly fledged from the academic nest, my first job, in the employ of my cerebral friend and his professorial client, was dumb, backbreaking labor, moving dirt with shovel and wheelbarrow. Which has left me to this day unable to distinguish the nobility of, or the essential differences between, shaping earth, laying brick, and joining wood, versus the parallel activities of the mind with words and thoughts."

You see, for the hopeless romantic, it's nostalgia that brings a heroin escape on the days when he feels dragged, kicking and screaming, from youth. It's the sound, the smell, the touch and taste that alights on the tip of his tongue, calling to mind at once the smallness of a single word, and the vastness of the universe. It's how he knows he's not alone.

Which brings me back to that day in June, and the nonchalance of Ed's "Oh, I don't know, whatever you want to do"—the simple truth of his having undertaken the adventure without an ounce of contrivance. It was Cora who finally suggested the activity that—now, one year past—strikes me as so perfectly apropos. "Why don't we watch *The Civil War*?" she said. It wasn't just that we were hot and tired, though we were. And it wasn't just that Ed had trouble walking that day, though he did. It was simply that, no matter the time or place, Ed loved sharing his passion for the past with his family and friends. And we loved it too. And so we sat together, the three of us, in amiable silence, engrossed in a beautiful story of a terrible time. It was all we needed. We were satisfied.

Later that evening, after a sumptuous feast at a little place in the East Village, with an absent-minded waitress who brought us one more salted caramel sundae than we really needed, Cora and I walked Ed to the corner and saw him into a cab. If we had known that the smile he gave us through the open taxi window would be the last we'd have for the rest of our lives, what would we have done differently? I've asked myself this question from time to time, having recently arrived at the age where one ponders the deeper ponderances of the universe. And here is my answer: Nothing. I would have done nothing different, I would have said nothing different, I would have spoken not a single word to fill an empty space that was quite naturally meant to be. Of that day, I would change nothing. Because, like Ed himself, that day was perfect in its imperfection. It was a wonderful, memorable dalliance, lighthearted and joyous in its promise of another and another and another. And, though our good-bye was short, uninformed as to the consequence of its brevity, it was a good-bye. And for that, I am thankful.

As I turn to the last page of the story of Ed, I find myself looking between the lines for the sage advice you could always count on him to offer. Perhaps it is simply this: In the grand scheme of things, we control very little. There isn't a single guarantee that the sun will rise tomorrow, no method by which we can accurately predict the course of our lives. But every one of us here has the gift of time—as much as we're allotted by fate, and not a second more. To spend it wisely, in pursuit of love, life and all the things that truly matter—as Ed did—is to honor the gift, however long it may last. In this, I wish you all the very best.

—Kevin Jacoby

The Mathematical Bridge At Queens' College, Cambridge

Photos and drawings © Philip Caston

1 Mathematical Bridge, Queens' College, University of Cambridge, designed 1748, built in oak 1749, rebuilt in teak 1905.

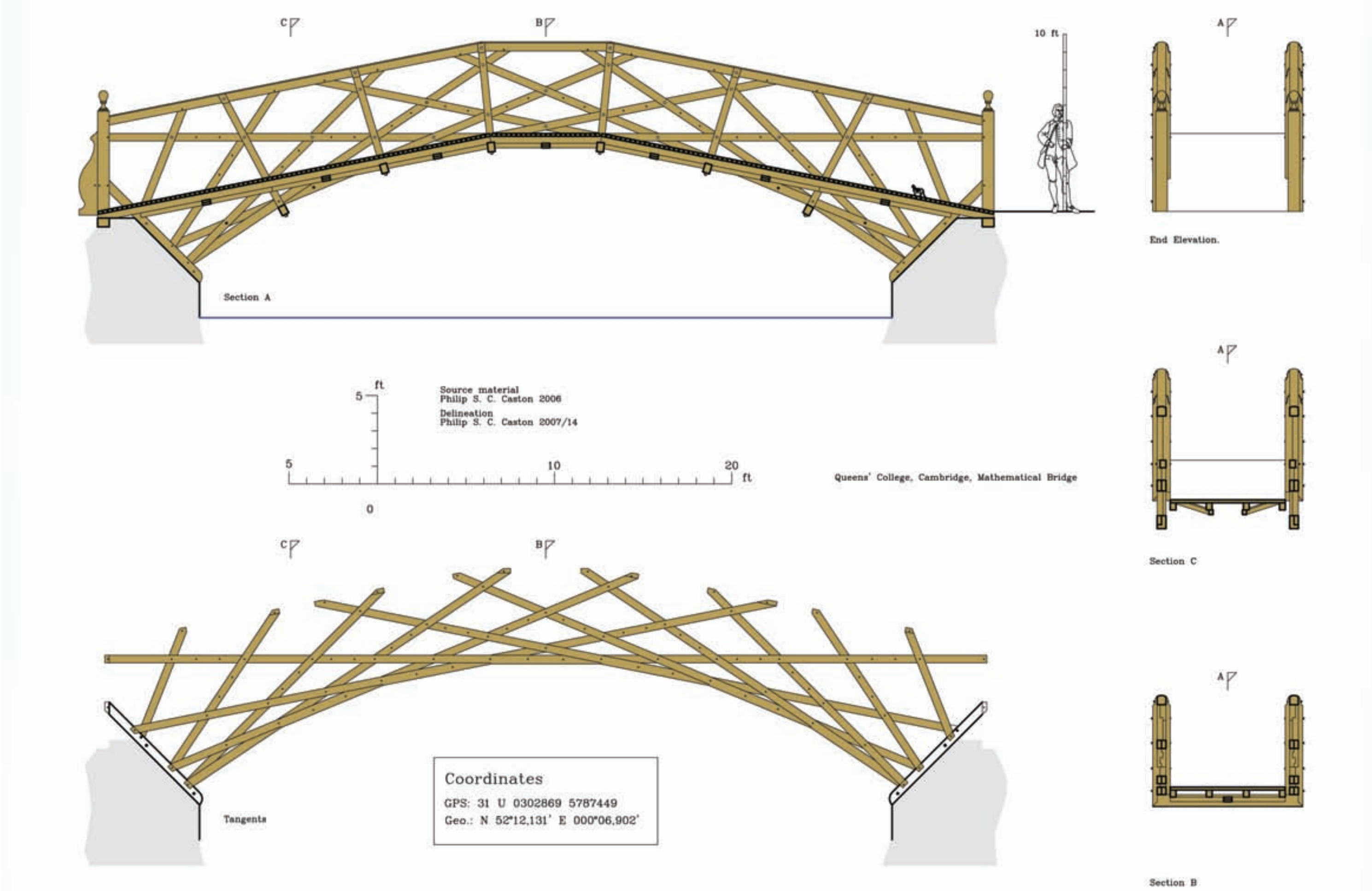
A VISIT to Cambridge in England would not be complete without punting on the river Cam, which meanders through the city. Whether propelling yourself or being chauffeured, this highly enjoyable experience takes you through the grounds of several university colleges and under several bridges. Sooner or later you will pass under the famous Mathematical Bridge in the midst of Queens' College, whose grounds lie athwart the Cam. Here you will see the bridge from the best possible angle to study the framing (Fig. 1).

Likely you will want to stop and investigate further. For a small entrance fee, anyone can gain access to the college and walk across the bridge to inspect its trussed railings close up. The bridge was executed in 1905 by William Sindall, a local carpenter, as a rebuild in teak of a 1749 oak predecessor, originally designed in 1748 by William Etheridge (1709–76) and built by James Essex (1722–84). Fig. 2 analyzes the framing elevation.

Sindall's replica is a faithful copy of the original wooden parts, except that the bolts were modernized, so that in effect the original 18th-century design and construction are conserved in their original setting but with younger materials. The bridge is fairly diminutive, just 50 ft. 7 in. long measured between the outside surfaces of the end posts, with an overall width of 8 ft. 6 in. measured from the outside surfaces of the radials (intermediate posts). The intrados spans 39 ft. 9 in., measured between the lowest contact points with the sills, and the bridge rises 6 ft. 7 in. from there to the crown of the intrados. The Mathematical Bridge has spurred the construction of several copies, in themselves all interesting structures, but none reaches the level of complexity or uses an important concept found in Cambridge's.

Etheridge's design uses two arched trusses set parallel to span the river between two inclined stone abutments. Floor beams span between the truss undersides and support stringers that make up two inclined ramps and a landing at the crown of the arch, which in turn support the floor deck. The design of the two trusses, which are symmetrical about the major axis of the bridge, has led to the bridge being called mathematical. The individual members are geometrically laid out and their precise angles of intersection calculated.

The inclined posts, called radials as they all point to a common origin, are set at 11.25 degrees to an adjacent radial and part of a 32-segment circle. The remaining diagonals, called tangents, are each set at right angles to an imaginary radial placed equidistant between pairs of real ones or beyond the actual ends of the bridge (Figs. 2 and 3).



2 At top, side and end elevations. At middle, framing and underpinning section. Above, floor and truss section, elevation view with radials, rails and posts removed to show tangents in geometrical position. Web gets thicker at intrados.

The tangents intersect each other in a regular manner and also are linked together by the radials. The resultant triangular shapes in the plane of the tangents make the trusses inherently strong and stable. This is a basic design concept later found in the Town lattice truss (after 1820) commonly used in North American covered bridges, though usually without elements to correspond to the radials. Some Town lattices in Québec, however, do add paired posts to the design, which clamp the lattice at intervals.

The Town lattice truss has essentially a straight rectangular form and can be manufactured to any length required. Accurate measuring of these lattices will normally reveal a camber, but it is negligible in terms of the effect on the basic geometry. The braces in these lattices are arranged in two separate planes. In each plane the braces are spaced out parallel to each other at regular intervals and at an angle relative to the chords. One plane is the inversion of the other and is set so that the two planes brush each other. The braces in each plane are pinned (often double-pinned) together where two surfaces meet.

The tangents in Etheridge's design could have been constructed in the same manner, that is, "braces" and "counterbraces" each in their own plane and brushing each other at the geometrical intersections. In fact, this was the solution chosen in the design of a slightly smaller copy of the bridge at Iffley Lock on the outskirts of Oxford (UK). The Cambridge solution, however, takes the intersections of the tangents to a unique and conceptually complicated level of carpentry—the tangents are interwoven with each other; they repeatedly change between two planes (Fig. 4).

3 Bridge as seen from riverbank within Queens' College, 2006.

4 Top rail, some 5 ft. above deck, is integral part of truss, transmitting forces to abutments along with interwoven diagonal members or *tangents*. Added round handrail rests on brackets below.

5

6

The interweaving of flexible elements to gain a stiffer structure has a long history. The origins are unknown, but can definitely be traced back to textile production in the Neolithic period. The first use in buildings is similarly uncertain, but was at least known to the ancient Greeks, who used wattled panels in their domestic buildings. The earliest recorded use of interwoven wooden members forming a heavy load-bearing structure is probably the Rainbow Bridge shown in the 12th-century *Qingming Shanghe tu* scroll in the Palace Museum in Beijing. The critical joints are not shown clearly, but an attempt to explain the weave was made in 1999 in a joint US-Chinese project by building a bridge for practical use in the old water town of Jinze in the suburbs of Shanghai (Fig. 5).

The weave of the Rainbow Bridge comprises longitudinal logs (the "warp") weaving around perpendicular transverse floor beams (the "weft"). If the weave were in a flat plane, then the longitudinal logs would have to snake between the stiff transversal floor beams, but by bending the weave into a segmented arch and selecting the correct spacing the warp can be constructed with straight logs. Instead of curving the logs around the weft, joints break up an otherwise continuous warp. This basic idea is used by the 100 or so Chinese covered bridges supported by a wooden arch still standing, as described in the last issue (see "Chinese Covered Bridges," TF 112), except that in those cases the log ends are not wrapped around the transverse floor beams, but rather jointed into them.

In comparison, the Mathematical Bridge truss weave is in a flat plane, and thus no clever segmental curving can avoid "snaking" the transversals. Also, the transversals intersect with each other at angles other than the perpendicular warp-weft pattern, making the solution an especially complex affair (Fig. 6).

In addition to determining which geometrical layout would work, the designer had to solve the problem of "snaking" the tangents. To understand the chosen solution requires a close inspection of the tangents. For this purpose the radials have been removed in the perspective drawing of the truss and show just two of the tangents, color coded according to their part location in a particular plane (Fig. 7).

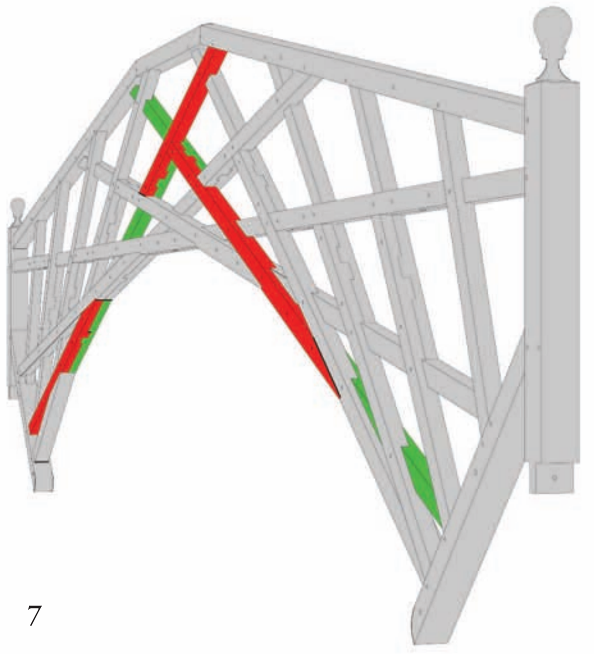
The lowest part of the right-hand tangent highlighted is in the outer green plane and set behind three other tangents. This single piece, tenoned at its lower end into the inclined sill, abuts at its upper end the next tangent piece in the same plane. The tangent then snakes its way into the inner red plane by having become a new single piece that now passes before three further tangents. It is scarfed at both ends to the tangent pieces in the outer green plane and additionally clamped in the truss by the bolted inner and outer halves of several radials we omitted from the drawing for clarity. The uppermost piece of the tangent is set in the outer green plane, making the tangent snake back to its starting plane, and tenoned into the underside of the top rail.

Meanwhile, the left-hand tangent crosses the right-hand one at the center of the truss. At that point the right-hand tangent has snaked back to the outer green plane so the left-hand tangent can only cross it in the inner red plane. Like its right-hand counterpart, it's divided into three sections—in fact the left- and right-hand sides of the truss are identical in every way and the individual parts could be interchanged. To make them fit together, a copy of one side has to be rotated about a vertical axis running between the two planes through the center line of the truss. This configuration is called *rotational symmetry* and is different from the *mirrored symmetry* generally found in framing work.

The advantage of rotational symmetry is that corresponding parts are identical and can be simply copied, which avoids thinking about "reversing" details. Etheridge may not have consciously been aware of any rotational symmetry, but just had to find a way to weave the pieces together. Having made one half of a truss, he could have copied it three more times to get two complete identical trusses. However, the second truss once in place is a mirrored version of the first, that is, the parts are the "reversed" version of the first truss.

In essence, the snaking was achieved by splitting the tangent up into short sections and setting these individual pieces into alternating planes. Etheridge could have chosen a much tighter weave by crossing two or even just one tangent before changing planes. A tighter weave would increase the weight of the truss, but also its strength by providing more uninterrupted cross-section length to the tangent. By weaving around just one tangent, a full cross-section along its complete length can be achieved.

The lighter weave that Etheridge chose, with its runs of half-section, allows for variations in the snaking. If we follow the system of changing planes after passing three tangents, at the top corners of the trusses we find that the final pieces of the first tangents in from their respective posts are in the "wrong" plane. It is not clear why Etheridge varied the scheme, with no evidence to suspect a mistake. The three-cross pattern we see in the truss is just a small piece of a much larger geometrical web that has an inner circular boundary at the intrados of the bridge truss and an external boundary where the rhombic or kite shapes can no longer



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5 Bridge at Jinze, China (N31°02.229 E120°54.948), near Shanghai, built 1999 for a PBS *NOVA* production demonstrating how *Qingming Shanghe tu* scroll's Rainbow Bridge might have been built. Straight logs envelop transverse floor beams. Some original logs have been replaced with steel pipe for strength.

6 Cambridge truss of all straight pieces has long horizontal tangent lying in outer plane in foreground, snaking to inner plane in next panel, then back to outer plane again to crown of intrados. Rotational-symmetrical equivalent of this half does the same, only in reversed planes. Two halves meet at intrados panel giving that part of tangent full thickness.

7 Perspective view of truss highlights weave of tangents between two planes (green and red). Tangents are identical except that one has been rotated about vertical middle axis of truss.

8 Tabled scarf joint in tangent is pinned as well as housed and clamped between bolted halves of radials.

9 Bolted-up radials also clasp shouldered tangent crossings and top rails. Suspended deck floor load is transmitted through radials to tangents and rails and ultimately to abutments.

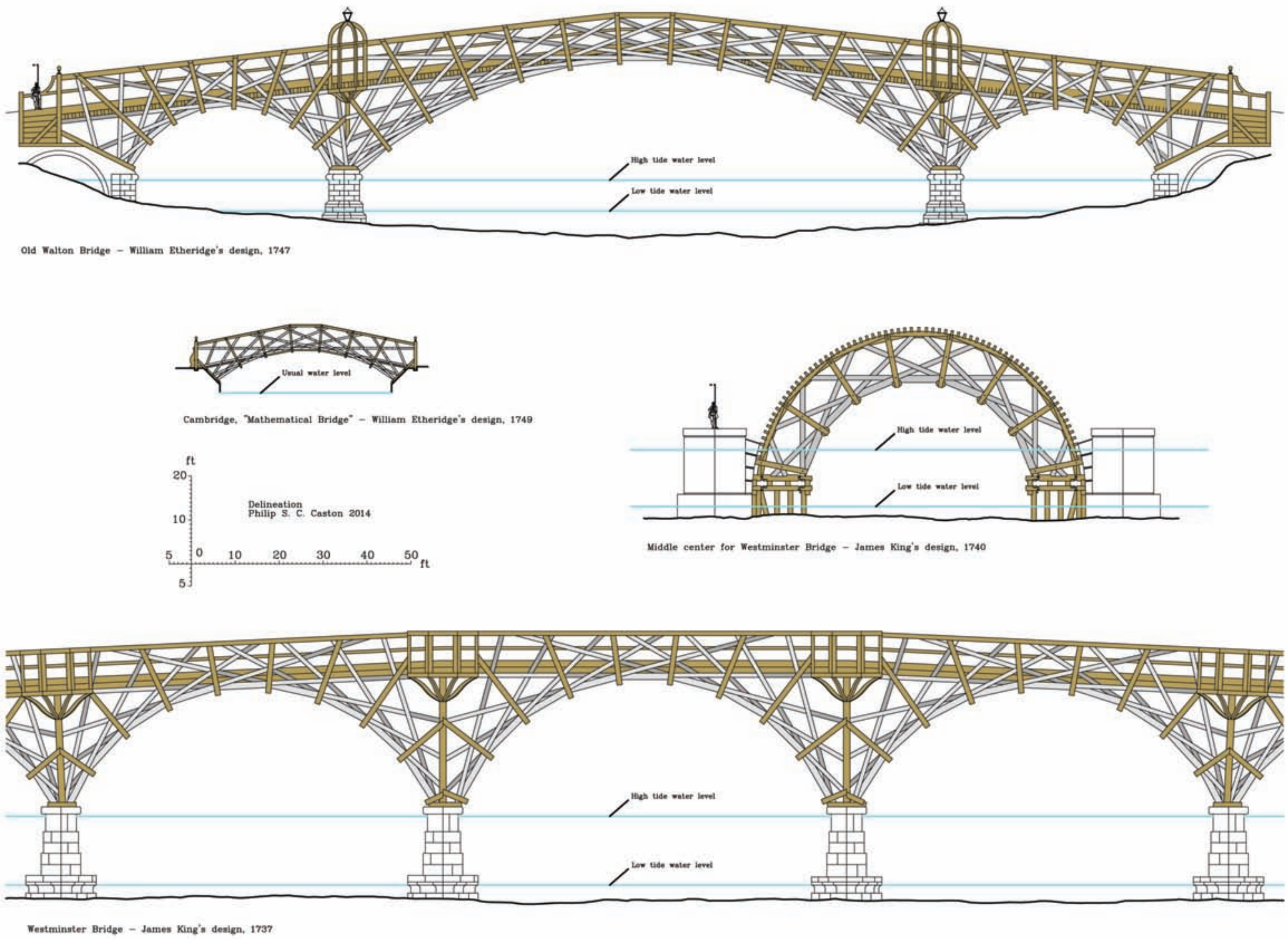
be formed by the tangents. This web extends around in a circle and repeats the pattern. The top corners of the truss as built in Cambridge extend into the web and should follow the pattern, but they don't. The case is the same for a bridge Etheridge had designed a year earlier at Walton-on-Thames, and it seems deliberate.

Of great importance to the structure is how tangents are axially spliced. The unique weave and the limitations of carpentry terminology make the splice elusive to describe. If each element of a tangent in its own plane is considered a full cross-section, then the staggered pieces can be viewed as cogged at their ends. If both planes taken together are considered to be the full section, then the term *tabled scarf joint* could arguably be used. Note well that this full section is formed only at the joint, however. The tabling is pinned by two wooden dowels (Fig. 8).

As the tangents are in fairly short lengths or sections and the laps and splices are all notched joints, assembly is a relatively simple process—the only possible difficulty being in selecting the right pieces! The tangent joints to sill, end posts and top rails are mortise and tenon connections, again pinned with wooden dowels. The final elements to be fitted then would have been the radials. These posts fit around the rows of tangent crossing joints in halves that clasp three crossings and the top rail together. The post-halves are notched to lap the inner and outer sides of the web of tangents respectively. When bolted together they lock up the tangents and supply additional stiffening as well as supports for the floor beams (Fig. 9).

What seems an urban myth surrounds the construction of the bridge—the belief that it can be taken apart without taking down the whole bridge. In large measure it proves to be not a myth. To test it, my undergraduate student Thomas Michelsen built two replicas of the bridge, one as a wooden model at a scale of 1:20 and one as a virtual CAD model. We used the digital model to disassemble the bridge part by part. Most of the pieces could indeed be removed individually, but some required other pieces to be disassembled first. The largest number of pieces that had to be removed together, however, turned out to be just three.

Where this was the case, enough structural cross-section in the tangents remained so that the bridge remained self-supporting. Just the inclined sills were a problem, but for their part they could be chopped out in halves with the bridge in situ and new halves inserted and bolted together, or the whole bridge could be raised a few inches with a jack, the sills slid off the tenons like removing shoes and new ones slid on. Thus the bridge can in fact be repaired in small steps, piece by piece, as the legend proposes.



10 At top, William Etheridge's Old Walton Bridge, Walton-on-Thames, designed 1747. Middle left, his Mathematical Bridge, Cambridge, designed 1749. Middle right, James King's centering for the stone version of Westminster Bridge, London, designed 1740. Above, King's unbuilt wooden design from 1737. Radials, handrails and floor are colored brown. Foreground tangents are colored light gray and background tangents dark gray.

While all the unique and clever features of the Mathematical Bridge are attributed to William Etheridge, a look at his career reveals some relevant influences. The first known bridge design with a similar truss was submitted by the carpenter James King (d. 1744) to the Westminster Bridge building committee in London in 1738 (Fig. 10, bottom, seen in part). The design was approved and timber for its construction ordered, but a bad winter changed the minds of the committee, who decided to build the bridge in stone instead. The design survives today in the form of an engraving held by the London Metropolitan Archives. Thirteen wooden woven arches can be clearly seen, drawn with shadows to accentuate the spatial position of the timber and reveal the two-plane woven design of the Mathematical Bridge. By 1743, Etheridge, then about 34, is known to have been working for King as his foreman on site. King was now engaged in building the centering for the arches of the stone version of Westminster Bridge. The centering (Fig. 10, middle right) seems to be a simplified and more massive version of the wooden bridge arch.

After King's death in 1744, Etheridge took over the business and built similar centerings to King's, asserting his to be superior. He was obviously a talented carpenter and is credited with the invention of a pile-sawing machine, improving King's method of striking the centers, and with saving the Westminster commissioners over £1,500. In 1747, Etheridge designed a three-arched wooden bridge at Walton-on-Thames, 25 miles upriver from the Westminster Bridge (Fig. 10, top). It was completed in 1750 and famous in its day, repeatedly reported on in magazines, appearing in countless engravings and painted on two separate occasions by the famous Italian artist Canaletto (Giovanni Antonio Canal, 1697–1768). The Walton bridge was torn down in 1781.

The design is clearly based on King's wooden Westminster Bridge construction, with woven tangents in the trusses that can be seen by the shadows in Etheridge's published design drawing. During the construction of the Old Walton Bridge, Etheridge worked on the design for the Mathematical Bridge in Cambridge, by which time he had gained enough experience with the weave to produce the complex design found in Cambridge.

While the design can be traced back through Etheridge to King's wooden Westminster Bridge, here the trail goes cold, and where it originated remains unanswered. It can't even be proven that King himself was solely responsible for the design. As owner of his company, King would put his name to any designs, but maybe (we may speculate) a bright young apprentice who would later take over the company was the real "mathematical" genius behind the design.

Other mathematical bridges built in the 18th century do not survive. A small footbridge in West Wycombe Park, Buckinghamshire, appeared in a 1787 engraving, and James Essex, builder of the 1749 Cambridge bridge, built a second one there called the Old Garret Hostel Bridge in 1769.

Two 20th-century mathematical bridges survive in England today, both easily visited. The Iffley Lock Towpath footbridge (N 51°43.744 W 001°14.428) near Iffley, Oxfordshire, built in 1924 in connection with the remodeling of the lock, is slightly smaller and obviously inspired by Cambridge's (Fig. 11). The design is by G. J. Griffiths, M.I.C.E., and dated November 1923.

It spans a boat-launch channel in the river Thames in a clear span of about 35 ft. The rise-to-span ratio of 1:5.9 is identical to the Mathematical Bridge's, as are the seven panels in each truss, and the radials again are set at 11.25 degrees to their adjacents.

Despite these similarities, there are differences in the detailing. The most basic is that the tangents in the Iffley Lock Towpath Bridge are not woven. The tangents are instead divided into two planes and, as at Cambridge, each plane is a rotational symmetrical version of the other around the vertical middle axis of the truss. In the inner plane the tangents are the continuous extension to the right of the intrados arch segments, simple straight pieces. This system is held constant throughout the truss and can be seen best in the middle of the truss, where the members are the longest and arch segment and tangent are connected together.

The second and younger contemporary bridge in England is in the garden of Wightwick Manor in Wolverhampton, West Midlands (N 52° 35.017 W 002°11.595), and is reputed to have been built in 1949. As a National Trust structure, it is open to the public. It appears to be over 10 ft. longer than the Mathematical Bridge, has a rise-to-span ratio of about 1:6.5 and generally uses a much slenderer section of timber (Fig. 12).

The basic geometrical idea, the use of radials and tangents and dividing the trusses into seven panels, is as used at Cambridge. The bridge has been repaired at some time with additional ironwork and later with further safety wires.

The tangents are divided into two planes and again each plane is a rotational symmetrical version of the other around the vertical middle axis of the truss. The similarities end there. The radials in this design are not two halves pinned or bolted together sandwiching the tangents as at Cambridge (Fig. 13), but instead single plank-like boards set between the two tangent planes. As the two tangent planes are separated by the thickness of the radials, they never physically touch each other and thus cannot transmit forces directly where they run by, but only at the junctions with the radials.

By contrast, the woven tangents in the Mathematical Bridge at Cambridge are enigmatic, complicated and practical at the same time, and they will inspire any serious framer to greater things. This scarcely appreciated gem reminds us that there is life beyond the ordinary. —Philip S. C. Caston

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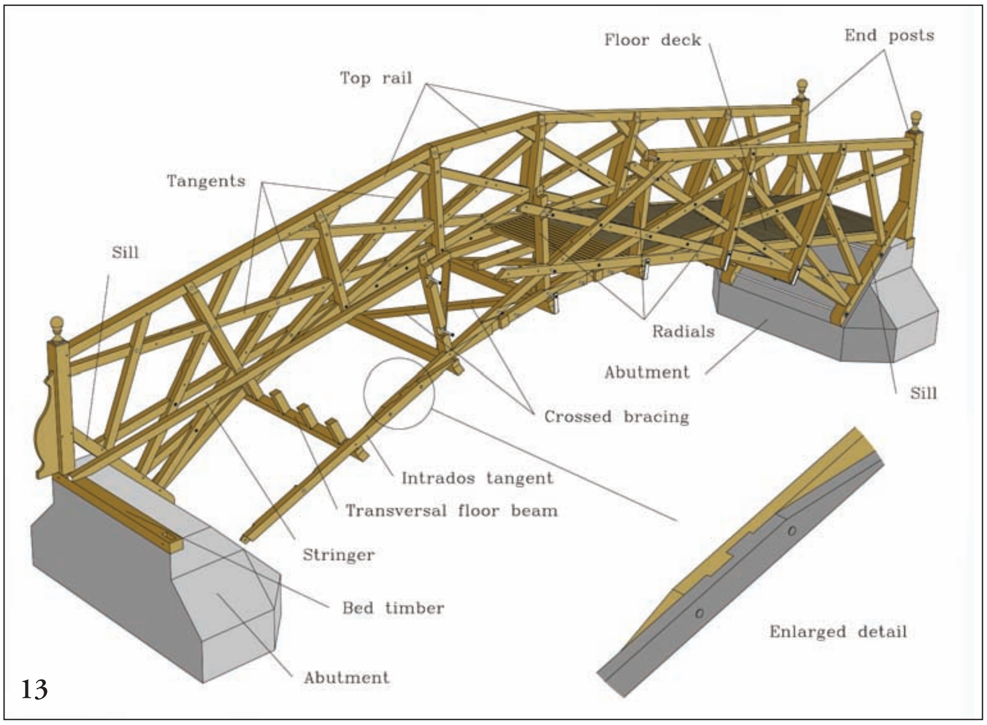
11 Iffley Lock Towpath footbridge, 1923, slightly smaller than its 1749 model and with similarly reduced scantlings. Transverse floor beams extend out under radials and are bolted up, departing from L-brackets in Cambridge, and crossed wooden braces are now metal rods.

12 Wightwick Manor footbridge, c. 1949, with slender-sectioned timbers not locked together through notches, repaired and strengthened with channel iron. Cables in open panels are nonstructural.



13 Cutaway of Cambridge bridge peels back layers from back to front to show structural elements, with rear truss shown in full. Floor deck is supported by stringers resting directly or indirectly on transverse floor beams X-braced and suspended from lower ends of radials. Load is passed to tangents and top rail, which transmits it via sill to abutments. Enlarged detail shows joint in tangent layers of intrados.

Grading Structural Timbers, New and Old

THE first-ever Timber Frame Engineering Council timber grading training course, hosted in April by the Heartwood School in Washington, Mass., was a sold-out, three-day event attended by sawyers, timber framers, engineers and architects. The range of professions represented at the course was a good indication of the broad interest in this topic and its importance. The days were divided between classroom and yard, where full-size timbers were available for grading, provided by sawyers Dave Bowman and Jim Rogers as well as engineer Phil Pierce.

Our instructors were Ron Anthony, wood scientist and president of Anthony & Associates, Inc., Fort Collins, Colorado, and Bob Falk, research engineer with the USDA Forest Products Laboratory in Madison, Wisconsin. Our trainers were Matt Pomeroy, director of inspection services for the Northeastern Lumber Manufacturers Association, and Don Pendergast, lead trainer for NeLMA.

Goals of the course A primary goal was to offer training specifically in the grading of structural timbers, but also to go beyond rote memorization and application of rules (not differentiating between new and seasoned lumber, for instance, or not interpreting requirements) to explain the technical basis for the grading rules.

While grading agencies and so-called third-party inspection agencies exist in all parts of the United States and Canada, timber framing materials differ from those of mainstream wood construction. Timbers often have not been graded by an approved lumber grading or inspection agency, as they were obtained from small sawmills that do not regularly employ graders. Some jurisdictions do not require grading of lumber. On occasion structures are fabricated from ungraded, unsawn timbers left in the round (logs) or from squared timbers converted by hewing.

Further, when antique or reclaimed timbers are used in timber-framed structures, they are typically not graded. There is no established, generally recognized approach to stress-grading timbers in situ (in place) in historic structures that are to be restored or repurposed. Yet there may be structural design reasons for wanting to verify the grade of a timber for a given structural application. These industry-wide characteristics justify a need for workers with a good understanding of grading rules and how to apply and interpret them, but who do not need the broader and more exhaustive training required of a certified lumber grader.

Workers for sawmills or timber framing companies can become certified lumber graders after a certain amount of training and payment of a monthly membership fee to a grading agency to cover the costs of monthly inspections and ongoing training, but they are only certified to grade at the specific mill or timber framing company and only for the size of lumber or timber for which they have been trained.

Becoming a certified lumber grader is not practical for those not working for a major lumber producer or for a third-party inspection agency, simply because the administrative rules and training requirements present a barrier to entry. Our timber grading training course was intended to provide education for those working at small mills or shops, or making grading decisions at a variety of sites but only periodically. There have been no established programs to fill this need.

In addition to training in the application of grading rules, a goal of the course was to consider the issues of grading reclaimed and antique timbers put to new uses, as well as timbers in an existing frame being evaluated for its load carrying capacity to accommodate new uses. These issues are relevant to timber framers working with salvaged materials and to architects and engineers conserving and adapting existing structures.

Overview of grading concepts *Wood versus timber.* Those words capture the central challenge of understanding the behavior of structural timbers and establishing safe working stresses for timbers in service. To help us learn what that phrase implies, Ron Anthony took us through the history of the development of established mechanical properties of wood and the development of grading concepts and standards. He showed us how to follow the thread from the American Society of Testing Materials (ASTM) D143 *Test Methods for Small Clear Specimens of Timber* to D2555 *Practice for Establishing Clear Wood Strength Values* to D245 *Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber*, and finally to the allowable stress values we see in the *National Design Specification for Wood Construction*, the *NDS*.

The practice of determining the strength of materials by physical testing goes back at least as far as Galileo and Newton. Naturally the more nearly ideal the material (that is, homogeneous and isotropic), the simpler the determination of the strength of the material. Wood offers considerably less than ideal behavior compared with a material like steel, but the behavior still can be quantified. Traditionally, small clear specimens of wood are tested to establish basic mechanical properties useful to us in design of beams and columns: bending strength (*Modulus of Rupture*, or MOR), tensile strength parallel and perpendicular to the grain, compressive strength parallel and perpendicular to the grain, and stiffness parallel to the grain (*Modulus of Elasticity*, or MOE). But of course full-size timbers of practical dimensions for construction are never made up completely of perfect wood. Trees often grow crooked, with some twist in the grain, and with branches, compression wood and other natural characteristics that result in sawn timbers containing knots, slope of grain, shake and other features that cause their behavior under load to vary from that of the clear wood samples used in laboratory testing.

Even within a given species, there is considerable variability in the results obtained from testing small clear specimens in accordance with ASTM D143. To establish safe upper limits on allowable stresses for a given species, it's important to have an understanding not only of the average strength of clear wood for that species but also of the degree of variability in a given strength property. ASTM D2555 provides us with tabulated values of the important mechanical properties of a whole range of commercial hardwood and softwood species along with the standard deviation from the mean strength value for the various properties. The standard deviation is then used to calculate the difference between the mean value for a given property and the 5 percent exclusion limit (that is, the value below which only 5 percent of the samples tested fell) that needs to be used for derivation of allowable stresses. This is a valuable foundation, but still only part of the story.

A real timber contains various features at different points along its length that cause it to behave differently from a piece of clear, straight-grained wood. In considering how slope of grain, knots, shakes and checks may affect the strength of a timber, it's helpful to think of the timber as a chain under tension: somewhere there's a weak link that will be the first to fail under load. That weak link in timber may be slope of grain that induces tension perpendicular to the grain (which has less than 10 percent of the strength of wood parallel to the grain). It may be caused by knots or groups of knots that reduce the effective section available to resist loads and that may cause some significant localized slope of grain as well. When that weakest link fails, the timber fails no matter how strong the other links may be. ASTM D245 is the document that formalizes the safety factors and strength ratios that account for the various growth "defects," defining for us how visible defects reduce the probable strength of a piece of timber relative to the small clear specimen values.

ASTM D245 also takes the values obtained from the D2555 tables and brings them down to a normal load duration, that is, C_D equal to 1.0. It goes on to provide adjustment factors for duration of load, moisture content, and other end-use variables that allow us to establish design values for an individual timber. D245 does not establish grades, however.

Lumber grades are established by rules-writing committees to market reasonably predictable lumber for structural applications and consistent visual appearance. For structural applications, grading rules provide a way of prebundling ranges of possible grade-limiting characteristics into discrete groups. These groups were originally called S1, S2, S3 and S4, but have been simplified to Select Structural, No. 1, and No. 2. In establishing allowable stresses for structural timber, we work our way down from the average strength values of small clear specimens by applying reductions for various maximum allowable defects within a given grade as well as by applying various safety and adjustment factors.

Grades then are a commerce-driven concept and are partly analogous to grades of steel for structural applications. Once we know the species and grade, we can look up the allowable stresses in the *NDS*. It certainly would be inconvenient and impractical if we all had to evaluate every piece of lumber for a structure and assess all of the strength-reducing characteristics case by case by applying the rules of D245. Ron Anthony, however, emphasized that we *may* do so if we wish. I will return to this practice as we discuss grading of timbers in situ. Ron pointed out that much of the timber harvested today is plantation-grown and is, therefore, of different quality from older material we often encounter as timber framers. Fortunately, we can still use the ASTM standards and small-clear-specimen data to determine structural grade and material properties of both new and old timber.

This approach to developing allowable stresses sounds somewhat indirect and theoretical, and in fact there is another way of determining allowable stresses for real lumber containing defects, that is, an in-grade testing program which relies on full-scale lumber tests to determine material properties. This approach comes from the opposite direction of the previous process by establishing the maximum defects permitted within a grade and then testing a large quantity of full-size specimens within that grade to determine allowable stresses. This process was incorporated into grading rules and the *NDS* in the 1980s to determine allowable stresses for dimension lumber. To date, it has not done so for structural timbers for practical and economic reasons.

Photos Tom Nehil

Don Pendergast, lead trainer for NeLMA, in action. At left, Ron Anthony, wood scientist. Both taught in grading course.

It's helpful to keep in mind that grading rules are commerce driven and address more than just structural requirements. Looking at the rules associated with a given grade of structural lumber (for example, No. 1 Beams and Stringers from the NeLMA grading rules), we see that some limitations relate to structural performance (for example, knots and slope of grain) while others are related more closely to appearance (pitch streaks and pockets, wane) and some relate to potential decay or insect damage (pin holes, stain).

A certified lumber grader working at the mill is in effect a policeman: he doesn't make the rules, he just enforces them. NeLMA as well as other grading organizations and mill graders are required to strictly adhere to the grade rules and are not allowed to deviate from any limitations of the rules unless specific interpretations permit. Graders and inspectors have no way of knowing the end use of a timber and cannot consider all the possible outcomes.

An engineer focusing on structural performance of a timber may find some of the rules superfluous (such as those relating to pitch pockets) and may choose to ignore them when evaluating grade-limiting characteristics for a piece of timber. That of course does not mean that the other characteristics identified and limited by the grading rules are not important to the end user, the building owner, and so they should never be simply ignored for convenience. Matt Pomeroy, NeLMA's director of inspection services, emphasized during the course that NeLMA in no way advocates modifying or ignoring certain grade rules when evaluating timbers. After material is inspected at full length and assigned a grade by an agency or certified mill, it would be the responsibility of the individual as a structural engineer to make any exceptions or determinations for their design, based upon their own knowledge of the grades, the limiting characteristics and the effects on strength.

Taking the above into consideration, grading rules for any particular job may be customized; the rules may be made more stringent or relaxed as ordered by the client. Checks and shakes at the ends of a timber might be prohibited entirely because of their possible effect on joinery, for example, but limitations on wane might be made more generous if acceptable to the client.

Any of us using the *NDS* to obtain allowable stresses for a given species and grade encounters the distinction made in the code between *beams and stringers* and *posts and timbers*. These classes are differentiated by the aspect ratio of timber width and depth. Timbers (of 5 in. minimum width in NeLMA Section 25.0) whose depth is more than 2 in. greater than their width are assumed to be bending members, whereas timbers (5x5 and larger, NeLMA 26.0) whose width is *not* more than 2 in. greater than their depth are assumed to be axially-loaded compression members. The allowable stresses listed are different because the grading rules used are different between beams and stringers and posts and timbers. This is nothing more than a simplifying assumption.

There is nothing inherently different about the wood in a timber just because it was sawed as an 8x8 rather than a 7x10. The living tree functioned both as a post and a cantilevered beam. In timber framing design, we know that beams and joists might be square in cross-section while posts might be markedly rectangular in cross-section. As part of customizing the grading requirements for a particular job, it is possible to request that all grading be performed following the rules for beams and stringers regardless of the aspect ratio.

NDS values for beams and stringers are typically slightly higher than those for posts and timbers and so naturally they are desirable as we start pushing timbers to their limits. Remember though that knots on the wide and narrow faces of beams and stringers are treated differently in their grading rules, and slope of grain is more tightly controlled.

One of the great advantages of grading timber at the timber framing shop is that decisions can be made on the spot as to how to modify a given stick before it is put to use. If the grade-limiting defect is located at the end of a stick, it may be possible to improve the grade dramatically simply by cutting off the offending portion, resulting in a shorter timber of higher grade. The grader working at the sawmill cannot apply such thinking since the end use and final length of the timber cannot be foreseen.

Grading timbers in existing buildings Engineers involved in conservation and adaptive reuse often find themselves needing to judge the load-carrying capacity of timbers in an existing building. There are key differences between grading green timbers coming off the saw and attempting to grade timbers in situ. According to ASTM D245 and all lumber-grading rules-writing agencies, strictly speaking it's not possible to assign a grade to a timber in place since all six surfaces cannot be viewed.

When examining timbers in situ, the investigator assesses visible defects that would exclude the timber from a specific grade. The more of the stick exposed to view, the better the judgment will be. For example, exposed joists and beams in buildings can typically be viewed along their full length on three surfaces, which doesn't leave a lot of room for defects to hide. Timbers in built-up assemblies where only one or two surfaces may be visible, and perhaps only for part of their length (for example laminated truss chords or Town lattice trusses), are more problematic, not only because defects may be difficult to detect but damage also may be hidden. In fact, condition assessment and grading are inseparable activities when examining timbers in place.

A key advantage to grading timbers in place is that it's possible to see exactly how the stick is being used and where the defects are located along the length. Large edge knots in an area of low bending stress may not be cause for concern. The "grader" is able to focus on the defects located in areas of high demand and that might cause failure under load, while at the same time largely ignoring most appearance-related aspects of the grading rules. (Can a pitch pocket really hurt you?)

In doing so, a clear understanding of the reasons behind the grading rules is needed, so that good judgments can be made as to which features need particular attention and which are of lesser concern. In particular, checks and splits, killers in grading green timber at the mill, may be of little consequence in an existing building in service (provided joinery is not adversely affected), since typically these features do not have major effects on performance and are already accounted for in the allowable stresses given in the *NDS*.

Certified graders from NeLMA and some other grading and inspection agencies in North America understand these issues and are willing to work with a framer, architect or engineer on site to assist them in identifying grade-limiting defects in an assembly of timbers in situ. The grader in these situations is not officially grading timbers since that can only be done on timbers with all six faces exposed to view. Their assistance in identifying features that might limit the grade of the timbers, however, will certainly add confidence and credibility to structural decisions.

Grading of reclaimed timbers The discussion of grading timbers in situ sets the stage for thinking about grading of reclaimed timbers salvaged from a structure. One often hears that old wood is much better, much stronger than the wood harvested these days. While the wood contained in certain species of timber harvested from old-growth forests in previous centuries may be better and stronger, timber grade always trumps wood quality, since defects can limit the load-carrying capacity of an otherwise beautiful stick. Mechanical damage (modifications) or damage from use and weathering also can have a major impact on the strength of the timber, no matter how fine the clear, straight-grained portions of the stick may be.

We should differentiate between two different grading practices for reclaimed timbers. Grading timbers sitting at the reseller's yard, with no certainty as to their final use, makes it unavoidable that we follow grading rules as written, treating mortises, notches and peg holes as if they were voids or knots (that is, areas of interrupted grain), and that the stick be graded at its length as found at the yard. Such treatment possibly grades a beautiful piece of timber as No. 2 or worse. On the other hand, if we grade the salvaged timber in a manner similar to that of grading in situ, where the use of a timber in a frame is determined, where we can know the spans and intended loads, where we can cut off defects or position mortises, notches, or deterioration at locations where the consequences are minimal, then we may be able to take advantage of the high quality of the remaining wood in the timber. Mortises and notches in such an application can be treated as mechanical alterations and we can turn to the Timber Frame Engineering Council *TFEC 1 Standard for Design of Timber Frame Structures and Commentary* for guidance how to quantify the effect of these notches on the strength of the timber. After all, we don't change the grade of a new timber when we cut mortises, drill holes or drive screws into it. As Bob Falk of the Forest Products Lab put it, "Why is a nail in a piece of lumber not a problem until we take it out?" Bob is asking in effect whether there is any more damage to the fibers after the nail is pulled than there was before, the answer being "not really." We don't consider a joist reduced in strength after we nail a ceiling to the underside, thereby poking holes in the tension face, or, more to the point, we don't change its grade.

Old-growth spruce timbers that might be rejected under grading rules for new mill-sawn timber. Use of ASTM standards or informed consideration of relevant grading rules might result in acceptance as structural timbers, with notches and mortises considered as they would be in a new timber frame.

Take-home messages While it was good to become more familiar with the grading rules as published by NeLMA, which are for the most part identical to those of all grading agencies in North America, it was also good to learn that there can be quite a bit of flexibility in the application of these rules, particularly when done by individuals with a good understanding of the why behind the rules. Grading rules can be customized for a given project, although defects that have consequences on strength, principally knots and slope of grain, cannot be overruled.

It's possible to hire representatives of NeLMA or other grading agencies and third-party inspection agencies, such as Timber Products Inspection (TPI), to guide you in applying the rules, especially those you consider important for a given project. They may not grade the timbers but will help you identify grade-limiting characteristics as you request and then let you make the call as to suitability for use.

Combining structural engineering with a good understanding of the grading rules and their foundation, that is, ASTM Standards D143, D2555, and D245, can put an engineer or designer in a powerful position to make informed judgments about the capacity of reclaimed or in situ timbers, much better in fact than a certified lumber grader who may have impeccable knowledge of the grading rules and how to apply them to green timber but lacks the training—or freedom—to consider how they affect the performance of timbers in a structure. As we learned from Ron Anthony during the course, this approach to looking at timbers in situ and evaluating reclaimed timbers is sound practice, not a quasi-legal corruption of the grading rules.

Future direction Rules for assigning grades to timbers in situ (really the process of trying to account for the presence of grade-limiting defects), in order to make possible the use of allowable stresses associated with the highest reasonable grades, have not been clearly formalized, to my knowledge. The document prepared by the Association for Preservation Technology and the National Center for Preservation Technology and Training, *A Grading Protocol for Structural Lumber and Timber in Historic Structures*, of which Ron Anthony was a principal author, lays a valuable foundation. Hastily made assumptions as to species of wood and grade, that document observes, can yield overly-conservative estimates that lead to unnecessary expense in strengthening and replacement of adequate members and degradation of the integrity of the original structure. Many of us have seen the wholesale application of steel plates to serviceable timbers in older timber framed buildings, for example. (Of course hasty assumptions can lead to *unconservative* estimates of strength as well.) To keep the document from becoming too complicated for the typical practitioner, however, the APT-NCPTT grading protocol stops short of laying out the more technical aspects of using ASTM Standards D2555 and D245, only presenting the background to the rules, the rules themselves and generally how to use them.

I believe it's important to establish as acceptable practice the application of the procedures of D245 to determine the actual strength reduction resulting from the features in a given stick, especially when it contains fewer and smaller defects than are permitted within a given grade. Equally important is to establish acceptable practices for applying structural analysis to identify stresses resulting from in-service loads and support conditions, and then to examine grade-limiting characteristics of the given timber at the critical regions along its length.

The timber grading training committee of the TFEC intends to offer the grading training course next in the spring of 2015. The course provides such valuable core information about our work and our medium that anyone associated with timber framing, from milling through fabrication and installation, stands to gain valuable insights. —Tom Nehil

Tom Nehil (tnehil@nehilsivak.com), a structural engineer and principal at Nehil•Sivak Consulting Structural Engineers, Kalamazoo, Michigan, is chair of the Technical Activities Committee of the Timber Frame Engineering Council.

Two Reciprocal Frame Gazebos

1. Square Timber, Eight-Sided Plan

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Photos Adam Riley

IN the spring of 2009, TF 91 began with a review of Olga Popovic-Larsen's excellent book, *Reciprocal Frame Architecture*. The reviewer, engineer Ben Brungraber, included photos of American reciprocal roof frames and recommended the book "to any timber framers still on their irresistible quest for another cool way to lose money." These fascinating structures and Ben's humorous challenge sang to me like sirens to a sailor.

For me, reciprocal frames conjure memories of M. C. Escher prints on my college dorm room walls and of structurally indeterminate systems from my engineering classes. Reciprocal frames can be elegant, inspiring and challenging to design and assemble. Popovic-Larsen defines a reciprocal frame as "a three-dimensional grillage structure mainly used as a roof structure, consisting of mutually supporting sloping beams placed in a closed circuit. The inner end of each beam rests on and is supported by the adjacent beam. At the outer end the beams are supported by an external wall, ring beam or by columns." I read her book cover to cover and began looking for opportunities to build reciprocal frames.

My first attempt was a simple three-legged stand for a large African drum. This was a chance to start small and sneak up on the topic. I used three 2x2 cedar legs 40 in. long, braced them at the required angles to cradle the drum (60-degree angle from horizontal, 120 degrees apart in plan) and scribed plumb and level bearing surfaces into the adjacent faces. I feared the drum would drive the joints apart or the legs would "unwind" under its weight. I was delighted to find that the weight of the drum actually tightened the joints and the slender tripod was remarkably stable, even with kids of all ages banging on the drum.

Not long after this experiment, a neighbor asked me to design and build a gazebo near a small pond on her property. She wanted something unique and beautiful which might someday be enclosed as a writer's cabin or a guest room. I showed her photos of reciprocal roof and floor systems and we agreed to incorporate those elements into the design, which eventually became the structure in Fig. 1.

Design I collaborated with two talented colleagues, Al Klagge and Jake Amadon, to design a frame in SketchUp using fir timbers on hand, with a 2D reciprocal floor and 3D reciprocal roof. There were several geometrical, joinery and assembly riddles to solve. Using available timber, we chose to build an octagonal frame with 8-ft. 5x5 posts and 12-ft. 5x9 rafters. The floor system would be repetitive: 12-ft. 6x8 joists would support each other in a single plane around a 36-in. opening and cantilever over concrete piers at each post location (Fig. 2).

We explored a few different roof slopes in SketchUp and found that steep roofs allow for a smaller framing aperture (or oculus, as it eventually became) but require the removal of more material from adjacent rafters than lower angled roofs. We wanted to preserve as much cross-section of the rafters as possible, so we settled on a slope of 6:12 measured along the axis of each rafter. Because the eaves are not level and the rafters do not converge on a central point, the roof slope varies depending on where it is measured and the roof segments thus curve slightly, although that may not be apparent in Fig 1. In other words, because the rafters are not parallel, the slopes of successive purlins differ. We used 2x6 purlins parallel to the eaves, which run over the timber rafters on one end and hang from the face of the adjacent rafter.

We chose to rotate the posts to keep them square to the rafters in plan. This made for compound brace housings on the sides of the posts, but that was easier to execute than compound joinery where the rafters meet the posts (cover photo). Since the rafters do not converge at the peak, that would have been necessary if we had oriented the posts toward the true center of the gazebo (square to the hips of a normal hexagon). If we were to build the gazebo again, I think we would rip pentagonal posts to make both brace and rafter bearing surfaces perpendicular to post faces.

The gazebo stands at the western base of 8432-ft. Teton Pass between Wilson, Wyoming, and Victor, Idaho, and at 6520 ft. it sees some extraordinary snow, wind and seismic loads. We knew there would be large shear forces where the rafters intersect so we wanted large bearing surfaces and plenty of relish beyond those joints to the ends of the rafters.

Popovic-Larsen addresses member and joint loads in her book and presents shear and moment diagrams to graphically display those concepts. While such analysis is beyond the scope of this article, good information may be found there if needed.

Raising and assembly challenges When it came time to raise the frame, the building site was deep with soft, sucking mud. After burying the forklift to its axles, we delivered timbers by hand while the mud tried to pull our boots off. The first seven floor joists teetered over the piers, scarcely able to hold themselves level. At this point a man's weight would have collapsed the assembly. It was not until the eighth joist locked the first and seventh together and provided some moment capacity that the whole floor system became quite rigid. What a relief! With that platform in place, we propped the first rafter at its 6:12 slope with a pair of 2x6 "kickstands" (Figs. 3 and 4). By design the rafters were directly above the reciprocal joists, and they all fit nicely until it was time to install the eighth and final rafter.

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1 Completed reciprocal frame gazebo, 14 ft. in dia., Victor, Idaho.

2 Floor framing. Eighth joist grants rigidity.

3 Rafter raising started on props.

4 Detail of stepped-notch joints in rafter assembly, with large bearing surfaces and adequate relish.

5 First and seventh rafters spread to allow insertion of eighth, Jake Amadon considering next move. Repositioning and application of appropriate force won the day.

6 Rick Neier and Jake survey completed and rigged rafter cluster from safe distance. Truck straps between slings and forks help set rafters level.

7 As expected, rafters spread slightly during raising. Posts lean out to receive them and tension will be applied to bring them plumb and rafters to 6:12. Ring of girts around post tops will maintain tension and may serve as window and door headers.

We knew we would have to sneak that last rafter between the first and seventh rafters and pivot it into position rather than dropping it straight down like all the others. The angle of the notched housing allowed for this but the twisted and out-of-square timbers did not. But Jake Amadon studied the matter (Fig. 5) and was ultimately persuasive. We were eventually able to get the forklift close enough to pick up the roof and lower it onto the posts for an eight-point landing (Figs. 6 and 7). It took some faith to work beneath this unlikely assembly and trust that our notches would hold it all together.

Estimating, roof framing and trim details In terms of job satisfaction and remuneration, this would have been a great place to stop. We basically broke even on the frame and learned a lot about reciprocal structures. But of course we had also agreed to provide the owner with a deck over the joists and a roof to shield her from the elements. Both were surprisingly hard to price. The decking, fairly straightforward, was less difficult: 2x6 cedar mitered on each joist to express the spiraling structure below, and a 36-in. octagonal parquet over the opening in the center. But the roof framing and flashing, on the other hand, were another time-consuming opportunity for learning.

Popovic-Larsen presents two approaches to framing and flashing reciprocal roofs. One is to express the structure inside and out with a faceted roof. Graham Brown, a designer and builder in the UK who coined the term *reciprocal frame*, is a proponent of this form. The other approach is to set the fascia level around the eaves and over-frame the roof with regular hips that hide the spiraling rafters from the exterior. The reciprocal designs of Japanese architect Kazuhiro Ishii and structural engineer Yoichi Kan employ this form beautifully. Popovic-Larsen provides extensive case studies of each.

Since our gazebo would initially be open walled and we had a limited budget to finish the roof, we chose the faceted form with a polycarbonate yurt dome over the opening at the center. This is where Ben Brungraber's challenge became prophetic. It took twice as long to frame and flash that roof as I had estimated (20 man-days, not 10). We learned more about curving roof planes and compound jack purlins—and we concluded that the level fascia and over-framed hips would have taken even longer to build!

Possible failure modes The gazebo's cedar shakes and unheated roof hold snow for months at a time. I've seen it over 4 ft. deep, looking like a big white mushroom. So far, the joinery and rafters have held up well through five winters, but the owner resisted my attempts at additional bracing or low shear walls, and I fear an earthquake or big wind event in conjunction with the snow load will someday topple this gazebo.

My other concern is asymmetric loading of the roof when snow melts off the south side in spring but remains deep and heavy on the north side. I've seen that load condition crush a neighbor's yurt by snapping a few rafters on the snowy north side of the roof. In most reciprocal designs, there is little or no redundancy in the frame. When one member fails the others will be loaded in unpleasant ways and fall like dominoes. Still, I encourage framers seeking inspiration and a challenge to explore reciprocal structures. Many beautiful forms await to be built, and there is much to be learned. —Adam Riley

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2. Round Timber, 12-Sided Plan

Photos Daniel Girard except where noted

RECIPROCAL roofs offer ample opportunity for bracing directly across the frame, in this case provided by forked-post joinery (Figs. 1 and 2), but they are trickier to brace around the ring. In squared-timber work, five-sided posts are necessary to avoid compound-angled connections. In our case of timber in the round, I considered affixing cables or chains from perhaps 3 ft. up the side of the forks down to the sills at 45-degree angles, but settled instead on shear walls every other panel.

In polygonal-plan buildings, there is a dance between more and fewer posts. With our 32-ft. diameter, 12 posts resulted in about a 10-ft. span for the outer purlins but a relatively crowded scene at the aperture in the roof. Dropping to eight posts, the next elegant number in terms of shear walls and openings, would have made for a more spacious connection at the aperture but a significantly heavier loading of the rafters themselves, along with a 15-ft. span for the outer purlins.

Because each rafter rests on top of its neighbor, while all the rafter butts are at the same height at the eaves line, any pitched reciprocal roof creates nonplanar segments defined by top of rafter (Fig. 2). Decking and roofing these twisted surfaces is a challenge. Tapered-width boarding over short lengths can help.

Generous overhangs offer a cantilever offset of the load in the primary rafter span, to the extent that the rafters are stiff enough to do so, perhaps reducing stresses in the aperture joinery. Pitch and aperture must be adjusted to work with intended rafter size,

1 At top, reciprocal-framed gazebo 32 ft. in diameter, winter-built of Eastern white pine logs in northern New England, purlins in place before roofing over. Forked posts provide transverse bracing, low walls shear bracing in alternate panels. Not part of original design, two-tiered stainless steel cupola 8 ft. 6 in. dia. covers aperture and will be supported by temporary posts during winter months to resist added snow load.

2 Above, tops of rafters bound twisted surfaces since peaks are stacked. Rings of purlins, to come, will shorten sheathing spans.

3 First two rafters supported by future temporary winter post.

4, 5 Challenge was getting innermost purlin ring for cupola to meet rafter peaks nicely. Initially rafters were tacked with structural screws. After assembling purlin ring, screws came out and the commander was used to adjust for best fit before replacing screws and adding heavy lags. Finally, rafter tips were trimmed in place at plane of lower cupola roof.

such that the joints where rafters cross have enough bearing while retaining sufficient material in the upper rafter. In this case, we chose not to remove any additional material from the flattened lower rafters at each crossing, though in other designs I have seen there is some notching of the lower rafter to provide a positive lock. Paired ¾-in. lag screws do that work here and allowed some positioning flexibility as described below. The flat cut in the underside of the upper rafters is swept (rather than notched) to full round section, to reduce shear stress (Fig. 3).

This is complicated geometry! Wondering how it would all fit, and needing the innermost purlin ring to meet the rafter peaks nicely, I considered leaving one of the innermost purlins uncut to be able to adjust on site. Ultimately I decided instead to make round tenons on the bottoms of the forked posts to allow them to rotate as necessary, and to precut the whole purlin ring exactly.

I assembled rafters to match scribe lines when raising but left them tacked with 10-in. structural screws, then assembled the innermost purlin ring, tacking to rafter peaks as I went. I then untacked all the rafter joints (all hands cleared the deck for this procedure, though friction kept the rafters from going anywhere on this relatively low 3:12 pitch) and used the commander to nudge the rafters to achieve the best possible fit with the innermost purlin ring. The ring meets each rafter peak cut with paired structural screws. The purlin ring itself has plywood splines at its butt joints (Figs. 4 and 5).

Setup for scribing the rafter-to-rafter joints was the most interesting shop aspect of the project. Originally I thought to simply set up the rafters at their final pitch with one above the other. Even with the low 3:12 pitch, however, that would have put the 24-ft.-long, 600-lb. rafters something like 7 ft. in the air at their peaks and required accurately holding them above floor layout and at pitch angle. My colleague Shannon McIntyre wondered, Why couldn't we scribe them flat?

Of course we could! I could take a pair of the rafters in SketchUp and rotate them down along the hinge point defined by the butt cut of the lower rafter until the latter's top surface was level. This left the upper rafter pitched both longitudinally and transversely. Then, in the 3D model, I built brackets to support the rafters in that attitude using the same crosspieces we had used in the rafter-to-forked-post scribe setup, with the lower rafter dropped 6 in. for scribing. In the layout of the real logs, with the support brackets screwed to the shop floor, the rafters cycled through, and alignment was taken care of by marriage marks on the crosspieces (Figs. 6 and 7).

The joints at the tops of the forked posts, meanwhile, required relatively straightforward scribing operations (Fig. 8).

Late in the game, the client decided to cover the large roof aperture, a smokehole for the central firepit, with an exhaust hood that would allow campfires even in inclement weather. We designed a two-tiered stainless steel cupola for the purpose and added a top purlin ring at the peak to carry it (Figs. 1 and 9). Under a 70-lb. snow load, and neglecting dead weight, the 8 ft.-6-in.-dia. aperture cover adds nearly 4000 lbs. to the inner purlin ring, or a 330-lb. point load at each rafter peak. While the frame could have been re-engineered to handle the situation and larger rafters ordered, given the seasonal use of the building we specified temporary supports to be installed each fall for the winter months.

—Josh Jackson

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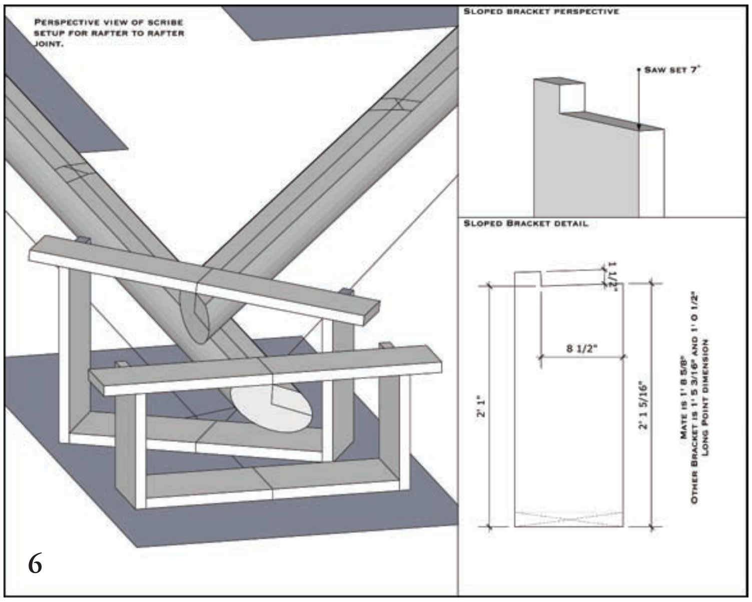

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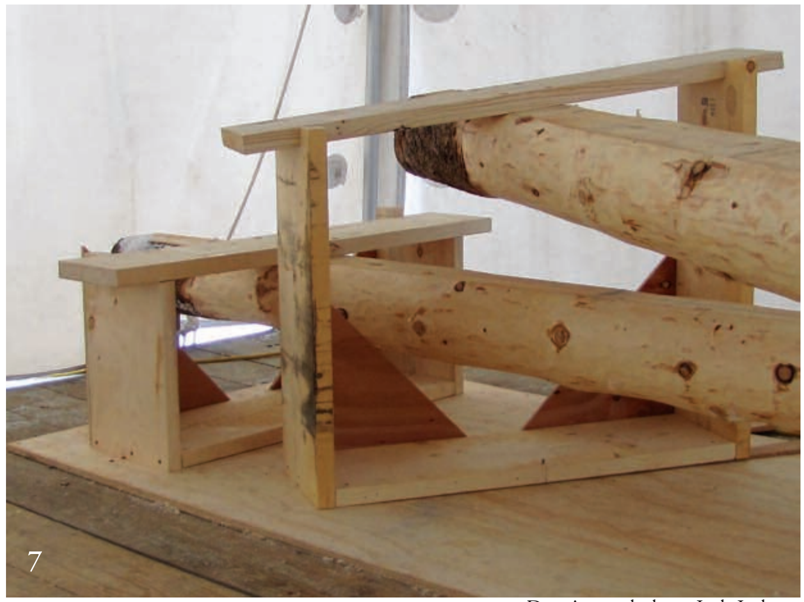

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Drawing and photo Josh Jackson

6 SketchUp drawing showing setup with support sticks and custom alignment jigs for rafter-peak scribe.

7 Jigs aligned to floor drawing with pair of rafters set in place, hanging from support sticks. Same sticks had been used earlier in scribing rafter to fork and were reattached to rafter using same holes.

8 Joinery at fork-to-rafter connection. Housing is cut square to mortise from scribe line as is tenon shoulder, providing accurate bearing while avoiding fragile shoulders and splitting tendency of coped joinery or sharp housing edges, and difficult router work of fully housed joints. Over time such joinery also performs well as pieces shrink, while fully housed joints in round work tend to develop large gaps.

9 Finishing up purlins and starting on shear walls. Twisted surfaces of roof can be seen most easily between upper two purlin rings and present sheathing fitting problems at cupola ring.

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Guild Conference Slide Show 2014

THIS year's annual conference slide show in August at Manchester, N.H., produced a crop of images of recent work by Guild members. A selection follows. Additional images will appear in the December issue of TF.

Photos Dermott Morley

Photos Adam Miller

Eastern white pine frame, 25x32 ft. 4 in., East Corinth, Vt., for woodworking shop with weaving studio above lighted by clerestory window. Note wedged tying joints. At right, red oak footbridge about 5x17 ft., with joints designed to drain, spanning Muskatequid Brook, Sudbury, Mass. Design and construction by Adam Miller, woodworker and weaver.

Below right, Douglas fir timber frame 28x48 ft. for residence in Raymond, Maine, built by Andy Buck of Brownfield. Architectural design by Andrea Warchaizer. Recess between roofs to be bridged by additional gable.

Left, screened porch with radial rafters over 8-ft. radiused corner, Leicester, Mass., with laminated plate and ties, designed by Dermott Morley and built by Dermott, Ian Anderson, and Jono O'Sullivan. Supporting peaks of seven rafters landing at center of arc was challenging. Photo at top shows neatly shingled corner at opposite end of porch.

Andy Buck

Cindy Mullen

Leslie Ayers

Above, timbers and above right, pavilion 18x100 ft. at Lexington, Va., to provide shade next to municipal swimming pool and built mostly of white oak by crew of Virginia Military Institute cadets, volunteer timber framers and students from MassArt, Alfred State University and Fanshawe College under leadership of VMI timber framing club, Cadet John Graves in charge. Design, engineering and working drawings by Cadet Nick Hounshell. Work was "productionized" to allow four-day completion by 140 volunteers who cut and raised frame and cleaned site in three and a half days.

Alex Greenwood

Right, Dale Emde and Sam Moyer placing Southern yellow pine hip rafters over 24x40-ft. hotel dining room of beach club at Abreu, Dominican Republic. Architectural design and timber frame by New Jersey Barn Company, Princeton. Frame design and engineering by the late Ed Levin with assistance by Fire Tower Engineered Timber, Providence, R.I. Roof frame needs to withstand hurricanes (frequent) and earthquakes (rare). Joinery was cut on site in beachside jungle.

Clark Bremer

Owner photo

Left, residence at Ft. Pierre, S. Dak., Eastern white pine timber frame 36x64 ft. with 32x8-ft. bumpout, designed by owner and framed by Northern Lights Timber Framing of Minneapolis. Sandbag dike on high side of house was built in anticipation of coming major flood from release at Oahe Dam on Missouri River in 2011.

New Energy Works

Right, detail of 3372-sq.-ft. summer residence on west shore of Lake Canandaigua, N.Y., framed in Douglas fir. Architectural design, timber frame and general contracting by New Energy Works, Farmington, N.Y.

Jeff Dean

Far left, hay and animal barn under construction in Homer, Alaska, using walls of old 15x19-ft. dovetailed cabin as core. Timbers are spruce, mostly beetle kill, corner posts from 40-ft. Douglas fir beach log. Design by Jeff Dean, framing by Jeff, Lee Carpenter, C. B. Corey, Taro Sasakura and Jerry Frederick. At left, central tenon on corner log passes through tie beam and enters rafter.

Ethan Lacy

Dennis Marcom

Left, exterior construction and interior finished views of 33x37-ft. panelized house 28 ft. high, built by Bensonwood, Walpole, N.H., and assembled on “postage-stamp lot” in Somerville, Mass. Architectural design by Santos Prescott & Associates, San Francisco. Above, detail of lakeside pavilion 20x32 ft. in Warren, Conn., Port Orford cedar framing by Bensonwood, with cherry splines and white oak pegs.

Dean Fitzgerald

Forebay barn for animal rescue and shelter and equipment storage, Montgomery County, Md., 78x36 ft. and 45 ft. tall. Oak and poplar timber frame, fir and poplar siding. Restoration by Heavy Timber Construction, Inc., Thurmont, Md. Abandoned building was near point of collapse, safe rigging was challenging. All lower-level 8x8 posts and 10x12 summer beams were replaced.

Jean Whelan Jim Kricker

Sloop *Clearwater*, built 1969, on barge in Esopus Creek, Saugerties, N.Y., preparatory to bow renovation in 2011–12. At right above, extensive stern rebuild undertaken at Kingston, N.Y., winter 2012–13. New rudder post 12x16, horn timber 12x12 to receive heels of frames, knee, and stern post 8x12 (with propeller shaft hole and bearing plate housing), all purpleheart; new white oak frames and planking. Allen Goldhammer, volunteer and longtime member of environmental group founded by the late Pete Seeger and others in 1966, who originally commissioned boat, looks on. Woodwork by *Clearwater* crew and Rondout Woodworking of Saugerties.

John Toates

Chesapeake Bay retreat, 18x30 ft., Prince Frederick, Md., for hosting crab boils and other family or social gatherings. Southern yellow pine framing, cypress cladding. Architectural design by John Toates, timber frame refinements by Jack Witherington and Andrea Warchaizer, engineering (for 90-mph wind) by John Ruff, P.E. Construction by Methods & Materials Building Co., Gilbertsville, Pa.

Jörn Wingender

Construction and finish detail of carport-entry 35 ft. wide for house and shop, Vallican, British Columbia, built in Douglas fir by Joern Wingender Traditional Timber Framing, Nelson, B.C. Center post receives four intersecting sloped plates paired in different plan view angles. Pitch changes by one-half degree from rafter to rafter for draped appearance of roof line between shop and house.

Rick Anderson

Ben Brungraber

Barn for dairy cattle to supply new attached cheesemaking facility, Churchtown (Claverack), N.Y., 80 ft. in dia., 54 ft. to peak of cupola, in Southern yellow pine. Timber framing by Tim Hilgendorff of Timber Hill Enterprises, Round Top, N.Y. Architectural design and overall project design by Rick Anderson of West Tisbury, Mass. Barn engineering by Joe Miller, Fire Tower Engineered Timber, Providence, R. I., shop drawings by Mike Beganyi Design and Consulting, Burlington, Vt. Barn has ten interior posts of peeled Southern yellow pine logs to resist buckling and three roof rings site-laminated from planks, with heavy timber floor framing connected by joinery and simple rods. One point of five-point star seen at left can be made out in top tier of roof in photo above.

Frame underway for residence in Vernon, Vt., 48x60 ft. (with a few jogs), by the Wooden House Co., Wells River, Vt. Timber frame in Eastern white pine, design by John Nininger and Gerald David of WHC, engineering by Katie Hill, P.E., The Structures Studio, Ferrisburgh, Vt. Visible timber faces surfaced with special drawknife and slicks. Longest timbers 46 and 50 ft., eliminating scarf joints; posts 12x12x28 ft.; one "Big Beam" 12x33x36 ft. to take roof load over open span. All knee braces form 3:4:5 standing triangles.

Adam Miller

Reflections on Embodied Energy

IT'S all about the envelope, stupid. I don't know if anyone in particular said that but I would add, in the same vein, advice offered by Rex Roberts, author of *Your Engineered House* (1964), a bible of the homesteader movement: "Let's say that a man wants to build a good house for his wife. The most important step toward success will have been to select the right wife." Brilliant HVAC systems, ingenious alternate energy, the latest in lighting, all mean nothing unless the shell of your house is effective.

Two kinds of energy are associated with houses. One is *embodied* (or embedded) energy, used to place, manufacture, assemble and finish a house (or any other structure). Included in this energy calculation is that consumed in the extraction and transportation of materials throughout the building process.

The other kind of house energy is *operational* energy, needed for cooking (3 percent), HVAC (50 percent), lighting (10 percent), appliances and electronics (10 percent), hot water (13 percent), etc. Lifestyle and location are major influences on these numbers.

Until recently, we thought that the energy required to make a product was insignificant compared to the energy consumed in the operation of that product, such as a building, over its life. Now we understand that the more efficient we make our timber and insulated panel houses, the more apparent the embodied energy becomes. In Europe, embodied energy numbers like 25 percent are being reported, in Australia and New Zealand 15 percent and in North America a range from 10 percent to 5 percent of the house's lifetime operational energy. These may be difficult numbers to calculate, but the case at the limit is not hard to understand: if a house uses 100 percent renewable energy for its operation, then the embodied energy to make it becomes the entirety of its net energy consumption!

We want to explore here the relationship between embodied energy and operational energy over the life of a house, since the former is a one-time investment that lasts as long as the house stands. To simplify, we will look at typical wall and roof systems and compare their embodied energy with the energy savings they can produce compared to predominant light-framed construction.

To put the whole-house relationship in perspective, it has been calculated that somewhere between 700,000 and 900,000 Btus of embodied energy are required to construct a square foot. This would mean a 2400-sq.-ft. house built in the northern Midwest might use $800{,}000 \times 2400 = 1.92 \times 10^7$ Btus (a really big number).

One striking image of how much energy it takes to build an average house is 13,500 gallons of gasoline (and, by the way, the figure for a Canadian neighbor's house would be 16,500 gallons). A small tanker truck carries about 5100 gallons, so that's about three US truckloads of energy-equivalent fuel per house.

The operating energy of this house over a 60-year life would differ according to construction: a code-built house would be something on the order of 13×10^9 Btus; an energy-efficient structural insulated panel (SIP) house would be on the order of 54×10^9 Btus. These are also really big numbers.

Houses of the late '60s and early '70s, before the 1973 oil embargo, did not regularly have air conditioning, were 1000 sq. ft. smaller, less energy efficient, used many unsafe materials (lead, formaldehyde and asbestos, for instance), had a higher content of "natural" materials resulting from a less sophisticated transportation system and cost about $25 per sq. ft. to build. According to the US Census Bureau, the total number of single family houses in the US in 1970 was about 44,800,000 and the calculated total consumed operational energy was about 216,800 Mbtus annually per house. In 2010 there were 77,701,000 single-family houses each consuming about 130,500 Mbtus annually. Of this, some 42 to 50 percent was used for space heating and cooling.

This looks like good news—more houses, less energy per house, and this with greater demands on our houses: larger, safer and healthier houses (fewer asbestos and lead issues), routine air conditioning, more glass, more light, lower maintenance, higher technologies (2 percent of our energy use is operating computers and associated cloud services), more appliances and designs to support more at-home activities—exercise rooms, libraries, home offices, baths for each bedroom, and so on.

The number of houses went up by 75 percent in 40 years and the average size went up about 1000 sq. ft. per house while the American household shrank by 18 percent between 1970 and 2003, from 3.14 people to 2.57, on average. The population meanwhile went from 179,000,000 to 309,000,000, a 72 percent increase, thus with more sq. ft. per occupant.

The consumed energy per house went down by 8 percent (was this due to fewer occupants?), but the total energy consumed in the US for single-family houses went up by 43 percent. This represents a lot of barrels of oil, international conflicts, tons of coal and contributions to climate change. If we add the embodied energy of houses built, the number becomes enormous and is not apparent on the US Census chart of energy "consumed." It is hidden in the commercial side of the statistics, such as manufacturing and transportation.

Embodied energy is expressed as energy/mass of product: megajoules (Mj, thousands of joules) per unit weight (kg) or Mbtus (thousands of btus) per unit of weight (lb). To convert between them, 1 Btu = 1055 joules and 1 kg = 2.2 lb. These values may be converted to energy per sq. ft. by using the appropriate fraction of the volumetric weight of a material. For example, oriented strand board (OSB), the popular sheet material, at 39 lbs. per cu. ft. works out to 1.65 lbs. per sq. ft. in ½-in. thickness.

I suspect the embodied energy of a newer house is substantially more than that of an older house, if for no other reason than that older houses used inherently more natural materials from more local resources.

Wood's embodied energy value is 8.5 Mj/kg while vinyl's is 77. It's easy to imagine 33 million additional houses with an additional 1000 sq. ft. each. If each house built requires 700 Mbtus per sq. ft. (henceforth *sf*) to construct, we end up with huge resource consumption. And we are not considering contents such as appliances, computers, furniture, furnishings, etc., nor the proportion of goods we consume today that must travel from Asia.

General assumptions To look at the information in a conversational way, let's say the average house has the 2400 sq. ft. we mentioned and one and a half stories, and that it's traditionally designed in a northern climate with 6500 heating degree days and 2000 cooling degree days. This is a typical Midwest climate these days. To compare heating and cooling energy consumption, we will use a conventionally built, code-approved builder-quality house, that might consume about 65,250 Mbtus for heating and cooling, or about 40–50 percent more energy than a SIP house. We assume the rest of the energy consumption is similar between the two houses.

We are timber frame junkies and, while there exist many SIP and hybrid panel enclosure systems (see Andrea Warchaizer's "New Enclosures for Timber Frames?" in TF 111), we will focus on the foam-core panel with OSB skins. These seem appropriate as the SIP is also a stand-alone building element offering the same efficiencies as it does with timber frames and other structural systems.

The enclosure is the boundary where the living environment we want meets the real world of weather. It's possible to calculate the manufactured and installed (embodied) energy of SIPs, as well as the energy saved in service (consumption), to demonstrate the impact on the total energy of a house during its life. It seems reasonable to exclude windows, doors, finishes, trim and so on, as these materials will be used on all systems. (It's true that wall thickness affects the volume of associated materials such as trim, but we ignore that.) We assume a timber frame supports the structure and is not included in the embodied energy of the wall system.

Of the practical common denominators, we will use per-inch R-values for (low-density) fiberglass of 2.2, cellulose 3.8, expanded polystyrene (EPS) 4.0, extruded polystyrene (XPS) 5.0, polyurethane (PUR) 6.5 and straw-bale 1.7 (average of 0.95 to 2.4. depending on more than we want to discuss here).

It would also seem reasonable that we compare as much as possible similar, practical systems, such as 6-in. EPS vs. 4-in. PUR SIPs vs. 2x6 fiberglass-insulated wall. Wall assemblies will be defined, an approximate R-value assigned, a per-sq.-ft. embodied energy value assigned, and a whole-house value calculated using our average house as previously defined, with an assumed wall area of 2200 sq. ft. and a roof area of 2400.

Examples All structural insulated panels (SIPs) in the following examples are sheathed in 7⁄16-in. OSB.

1. Wall SIP of 5½-in. EPS, including adhesives, top and bottom plates with associated R-value of 31; includes gypsum, wrap, strapping and siding. Embodied energy: 490 Btus/sf for all-wall value of 1,062,000 Btus.

Roof SIP of 9½-in. EPS including adhesives, with associated R-value of 45.5; includes interior gypsum, exterior adhesive, ice and water shield, cold-roof strapping and sheathing and 250 lb.-per-square asphalt shingles. Embodied energy: 1100 Btus/sf for total roof value of 2,623,000 Btus.

Comment. It's fair to say that this one-time investment of 3.7×10^6 *Btus will save about* 30×10^6 *Btus annually given efficient HVAC equipment, or a payback in 10 years.*

2. Wall SIP of 3½-in. PUR including adhesives, top and bottom plates with associated R-value of 28; includes gypsum. Embodied energy: 440 Btus/sf for all-wall value of 961,000 Btus.

Roof SIP of 6½-in. PUR including adhesives, with associated R-value of 48; includes interior gypsum, exterior adhesive, ice and water shield, cold-roof strapping and sheathing and 250 lb. per square asphalt shingles. Embodied energy: 1075 Btus/sf for total roof value of 2,579,000 Btus.

Comment. It's fair to say that this one-time investment of 3.5×10^6 *Btus is less than EPS and will save about the same annually given efficient HVAC equipment, or a payback in slightly less time than the EPS assemblies.*

3. Straw-bale wall with stucco scratch coat, 16x23x42-in. straw-bale, 10x16 box beam on top of bales, stucco scratch coat inside, with associated R-value of 30.5. Embodied energy: 82 Btus/sf for all-wall value of 180,000 Btus.

Roof framing of conventional light frame materials, sheathing, 12-in. cellulose ceiling insulation blown into cavities, vapor barrier, ½-in.-sheetrock ceiling, with associated R-value of 48; ice and water shield, cold-roof strapping, sheathing and 250 lb.-per-square asphalt shingles. Embodied energy: 682 Btus/sf for total roof value of 1,638,000 Btus.

Comment. It's fair to say that this one-time investment of 1.8×10^6 *Btus is the lowest yet and, with similar R-values, has a payback of less than a year.*

4. Light-frame wall of 2x6 studs, 6-in. fiberglass, 7⁄16-in. OSB sheathing and top and bottom plates, with associated R-value of 23; includes gypsum, vapor barrier, wrap, strapping and siding. Embodied energy: 260 Btus/sf for all-wall value of 571,000 Btus.

Roof framing of light frame materials, sheathing, 12-in. cellulose ceiling insulation blown into cavities, vapor barrier, ½-in. sheetrock ceiling, with associated R-value of 48; ice and water shield, cold-roof strapping, sheathing and 250 lb. per square asphalt shingles. Embodied energy: 682 Btus/sf for total roof value of 1,638,000 Btus.

Comment. This one gets tricky. The quality of a contractor-built house that meets code is the question. The embodied energy investment is 2.2×10^6*, more than a straw-bale assembly and less than a SIP assembly.*

In their new book, *Making Better Buildings: A Comparative Guide to Sustainable Construction for Houseowners and Contractors* (2014), Chris Magwood and Jen Feigin explore the decisions we might make that may have little effect on the operation of our houses and yet might make a huge difference on the impact of embodied energy in our houses. Often the choices are simple but require research.

There are those who suggest that a wood frame house has 12 times the embodied energy of a low-impact straw-bale house. We do not know all the specifications or inclusions, but there are choices and we need to look at them. The numerous charts of embodied energy by material show differences in their values, but collectively, as presented in the table at right, they give us an idea of the order of embodied energy for a range of common materials.

As we quickly see, good old unseasoned wood, the "prince of building materials" (Rex Roberts again), leads the way in both sustainability and embodied energy. Bricks are next at two times (some say four) the embodied energy, then kiln-dried and fabricated wood (millwork) at four times, concrete at four or five times, glass at 8 to 14 times, steel at 12 to 24 times, plastic at 6 (some say, but others say up to 45 times), and aluminum in there at something between 100 and 125 times!

If we look at embodied energy as a major factor in our building decisions, we see that natural, low-density materials will save embodied energy as well as being relatively decent insulators. In masonry, brick at R-0.2/in. is better than stone and concrete at 0.08/in. This may also tell us that careful considerations for materials with high embodied energy, such as rigid foam insulation, can have positive values in the long haul of ownership.

Lightweight building materials often have lower embodied energy than heavyweight materials, but in some situations lightweight construction may result in higher energy use. Where

MATERIAL	Mj/kg	Btus/lb	Btus/sf
Timber/lumber	8.5	3.7	12.8
KD timber/lumber	10.4	4.5	11.2
Green sawn wood	2.0	3.2	2.2
Glulam timber	12.0	5.2	16.4
OSB	11.0	4.7	7.7
Plywood	15.0	6.5	10.2
EPS	8.1	38.3	76.7
XPS	94.5	40.7	91.6
PUR	101.5	43.7	109.3
Cellulose			
(range 0.95–3.3)	2.1	0.9	0.14
Fiberglass	28.0	12.1	0.04
Cork	26.0	11.2	7.0
Straw bale			
(range 0.25–.917)	0.6	0.3	
Mineral Wool			
recycled	21.0	9.0	
Steel			
with recycled content	21.0	9.0	
Aluminum			
with recycled content	155.0	66.8	
Copper	100.0	43.1	
Galvanized steel	38.0	16.4	
Glass	15.0	6.5	
Concrete	1.3	0.6	
Fiber cement siding	4.8	2.1	
Brick	3.0	1.3	
Sheetrock	6.8	2.9	
Paint, water based	59.0	25.4	
Paint, oil based	97.0	41.8	
Wallpaper	36.0	15.5	
Wool carpet	106.0	45.7	
Ceramic tile	12.0	5.2	
Vinyl flooring	66.0	28.4	
Plastics, general	90.0	38.8	
PVC avg	77.0	33.2	
PV (monocrystalline)	4750.0	2046.5	
PV (thin film)	1300.0	560.1	

heating or cooling requirements are high, their use may raise the overall energy requirements of the building.

Conversely, for buildings with high heating or cooling requirements, but located where there is a large diurnal-nocturnal temperature range, heavyweight construction (typically with high embodied energy) such as adobe in the Southwest, used together with high levels of insulation, can offset the energy consumed for the building. Since embodied energy must be considered over the lifespan of a building, in some cases a higher embodied-energy building material or system may be justified if it reduces the operating energy requirements substantially. A durable material with a long lifespan such as aluminum may be an appropriate material selection despite its extremely high embodied energy.

—Stewart Elliott

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