Longitudinal Wood I-Beams

by Lamar Henderson

Drawing a simple arc on an elevation can change the entire approach to the design and construction of a project. At least that's what happened with the Gottlieb/Davis remodel. Dan Gottlieb and Peggy Davis had originally wanted a kitchen remodel and greenhouse addition to their house in Palo Alto, California. But after analyzing their programmatic needs, the existing residence and site, as well as property values in the neighborhood, we agreed that a more extensive remodel was appropriate.

The general massing of the house took on the appearance of two row houses, each reflecting a different living zone. One became the private zone: the bedroom area with a pitched roof. The other was the public zone: living, dining, kitchen, sunroom, second-story library and a bridge to the other side. We jokingly referred to the public space as the grand hall. In the search to find a dramatic roof for the grand hall, I sketched a barrel-vault ceiling and changed the course of the project.

I submitted the barrel-vault design to Dan and Peggy as one of three proposals. They were apprehensive, but at my suggestion, they decided to build a scale model, and once they were able to visualize the design, the barrel vault became the obvious choice.

We knew that the complexity of building the vault would either deter some contractors from bidding on the project or would result in highly inflated bids. So after a thorough discussion, Dan and Peggy and I decided to build the project ourselves.

Design dilemmas—Conceptually, the grand hall is a basilica with a nave and side aisles. The aisle on the south became the entry, stairs and sunroom. And the loads from the vault would flow through the wall to the foundation. The northern aisle, however, was problematic. Due to the constraints imposed by the floor plan, there were no walls that could take roof loads directly to the foundation. A typical strategy of using a curved truss at intervals to shape the vault would require a very large and heavy beam to carry the loads to the end walls. I had to find an alternative solution.

The elevations of the two end walls dictate the shape of the roof and interior space, so it seemed logical that the structure should span the length of the hall with loads flowing down through these end walls. The problem was to find a structural member that could span 36 ft. and yet be light enough to carry by hand. A glulam beam, for example, would have been too heavy.

The metaphor that the vault was, in effect, a floor of parallel joists in the shape of a circle, suggested that some form of lightweight wood truss could span the distance. After considering the cost and weight of various engineered components, I decided on wood I-beams with solid-lumber flanges and oriented strand-board webs purchased from Structural Development, Inc. (SDI, P.O. Box 947, Los Gatos, Calif. 95031).

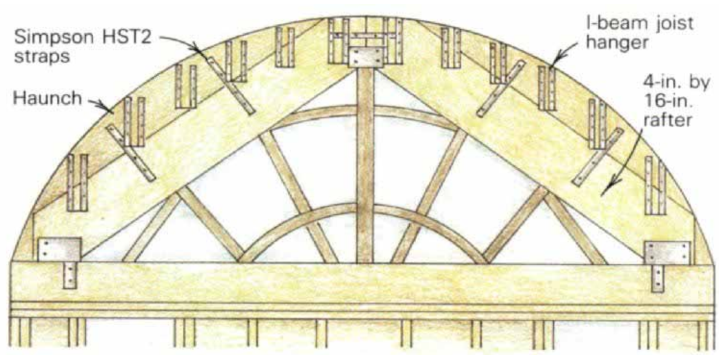
Attaching the I-beams to the end walls was no problem because manufacturers of metal connectors for wood construction have developed special hangers for I-beams. Developing a blocking system to tie the long I-beams together was more of a challenge. When I initially laid out the I-beams on the end wall, aesthetics ruled over good engineering. I called for the I-beams to be laid out radially so there would be a flat surface to which to attach the exterior roof sheathing as well as the interior drywall. This created a problem because I-beams, though strong when loaded vertically, are flimsy when loaded horizontally. I planned to solve this in part through the use of blocking, cut to the curve of the arc between adjacent flanges.

When the project passed through the Palo Alto building department, the plan checker asked for a more detailed analysis of the shell structure, especially the rotation of the beams in their weak axis and the behavior of the entire roof assembly. To find out how to do this, I contacted the American Plywood Assoc. (P. 0. Box 11700, Tacoma, Wash. 98411). The call turned out to be the nadir of the project. One of their engineers said the structural system should be analyzed as a curved stress-skin panel. Not only would this be mathematically complicated, but fabricating such a panel in the field to achieve the assumed structural values would be very difficult because the plywood would have to be glued to the frame under pressure.

To eliminate the need for a shell analysis and deal with the problem of having the I-beams in the weak axis, we rotated all the I-beams in their vertical axes, thus maximizing their value as structural members. Now, the problem was to create an outside curve that would allow the roof diaphragm to work, and an inside curve would create the barrel-shape ceiling.

Two-by blocking could be cut to fit the shape of the curve and attached perpendicular to the I-beams with Simpson H4 metal anchors (Simpson Strong-Tie Co., Inc., P.O. Box 1568, San Leandro, Calif. 94577). This would make the top flanges of the I-beams rigid and create a curved surface to glue and nail the plywood. However, the bottom flange and portions of the I-beam could still move laterally. We figured the bottom flange could be made rigid by using some type of metal strapping as bridging.

Because of the way the I-beams were being installed, the bottoms



Drawings: Michael Mandarano

of the beams would not line up in a smooth arc and would not work as a nailing surface for the drywall ceiling. However, a quick review of the *Gypsum Construction Handbook* (United States Gypsum Co., 101 S. Wacker Dr., Chicago, Il. 60606-4385) showed a commercial system that would work for us. It employed cold-rolled steel channels and steel furring channels as a method for creating the interior vault.

After correcting the drawings, we resubmitted them to the building department for final approval. The building permit was issued and construction began.

Beaming up—The first order of business was to order the two curved glulams that would shape the end walls. We sent a drawing to a local glulam fabricator, and the bid came back at just under $6,000. Why were the glulams so expensive? Apparently, the diameter was less than the minimum allowed by the fabricating jigs, using ¾-in. stock. In order to make the glulams at such a small radius, the laminate had to be ⅜ in. thick. Material any thicker would have failed in bending.

The cost was too high. We finally solved the problem by using a pair of 4-in. by 16-in. timbers (select structural Douglas fir) as rafters, with separate pieces (called haunches) shaped to the curve of the vault and bolted on top of the rafters (drawing facing page).

The next step was to make a template of the end-wall elevation that we could use to lay out and fabricate the windows. We laid out four sheets of ½-in. plywood and struck a radius for the outside edge of the vault as well as for the head and sill of the windows. Next I drew the center 4x4 column, then the other 4x4 members dividing the window frames. I drew the width of the 4x16 rafter, locating the curve and the haunch. All metal connectors such as the straps for the haunch and the hangers for the I-beams were also located on the template.

We cut out the plywood template, including the window openings, with a portable jigsaw. After carefully marking the pieces of the template and setting them aside, we sent the window cut-outs to the window manufacturer to use as templates for the glass.

The floor space of the second-story library was big enough to lay out and prefabricate the end walls of the vault. We cut the rafters and their haunches with a 7¼-in. worm-drive circular saw, cutting partway through from each side. We found, however, that we had to have two saws: while one was in use, the other was cooling off.

After all the pieces were cut, the end wall was assembled, checked, bolt holes were drilled for the haunch straps and hangers were located for the I-beams. First we installed the center 4x4 post, followed by the left and right 4x16 rafters, the haunch, which was bolted down using Simpson HST2 straps, and the 4x4 frames for the windows. Finally, the hangers were nailed to the rafter/haunch assembly. As the end walls were being cut and installed, the blocking and shims were being mass-produced.

With the end walls in place, it was time to install the I-beams. We started with 18-in. deep I-beams, one on each side of the vault. The length was carefully measured on each side to verify that the end walls were square and plumb. We cut the I-beams and nailed web stiffeners at the end bearing points. (Web stiffeners are vertical pieces of 2x4s cut to fit between the upper and lower chords of each truss.) The 36-ft. beam weighed approximately 150 lb.; four people could easily maneuver it into place. The next beams were 16-in. deep, weighing about 144 lb. each. The eight remaining beams were 14-in. deep and weighed about 137 lb. each. We installed the curved blocking (16 in. o. c.) and shims as we went along in order to stabilize the I-beams (photo below). Then we crisscrossed the I-beams with metal strapping on the upper and lower flanges every 32 in. to stabilize the beams even further. At the suggestion of Kurt Anslinger from SDI, we used plumber's tape (the metal strapping that plumbers use to hang pipes) for this, which worked just fine.

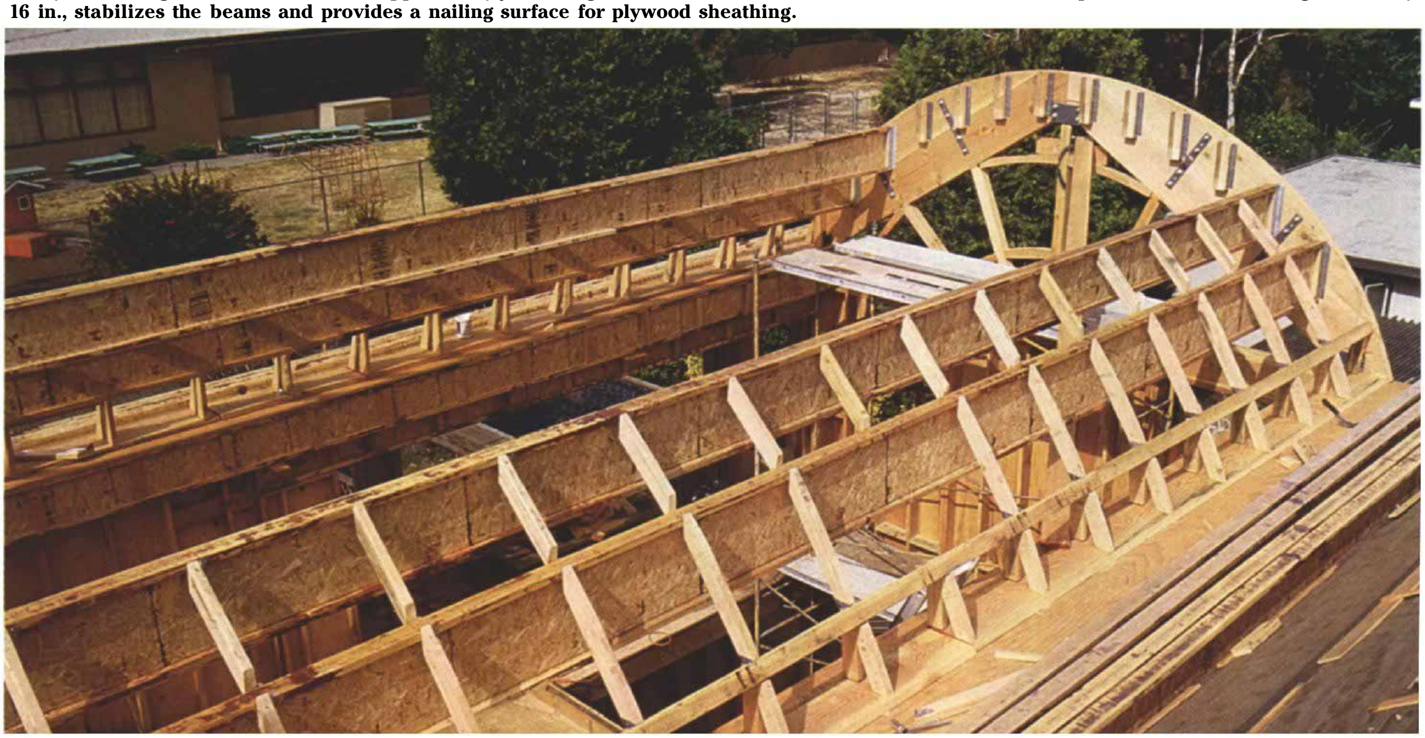
According to the American Plywood Association, ½-in. plywood bent widthwise has a minimum bending radius of 6 ft., and that would work for this roof. We nailed down the sheathing with 8d ring-shank nails to the beams and to the blocking. Between the courses of blocking where the plywood edge had no support, we used H-shaped plywood clips to tie adjacent sheets together.

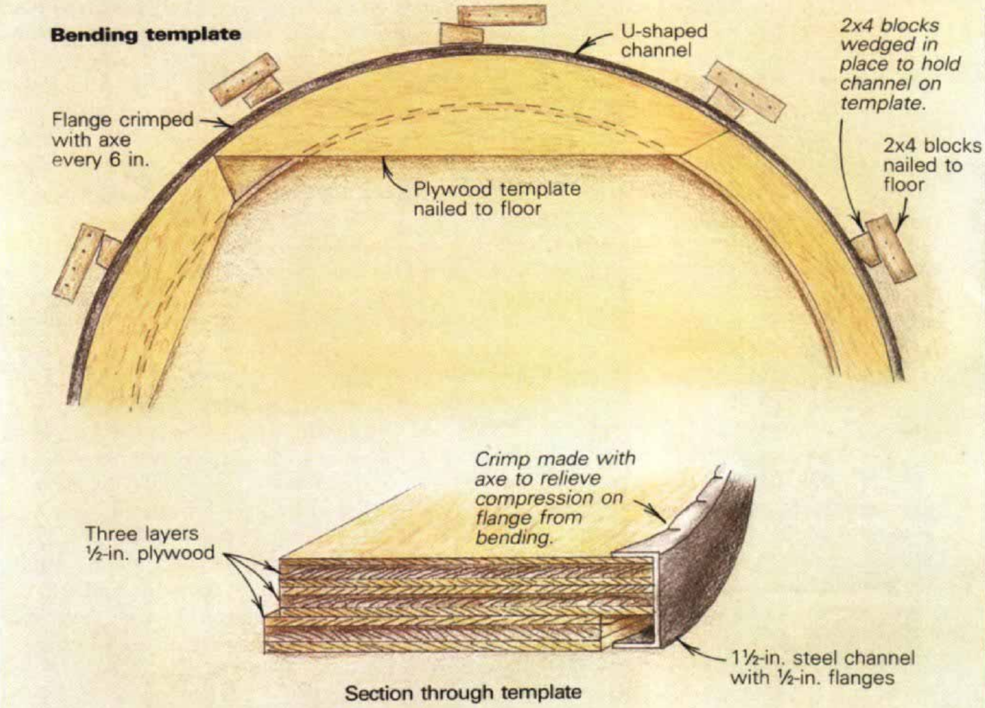
Before we started the interior finish work, we heeded another bit of advice from Anslinger and used duct tape to wrap the strapping where the crisscrosses touched each other. As the building moves, he had told us, the straps could rub against each other creating a bothersome noise that would be hard to fix once the ceiling was in place.

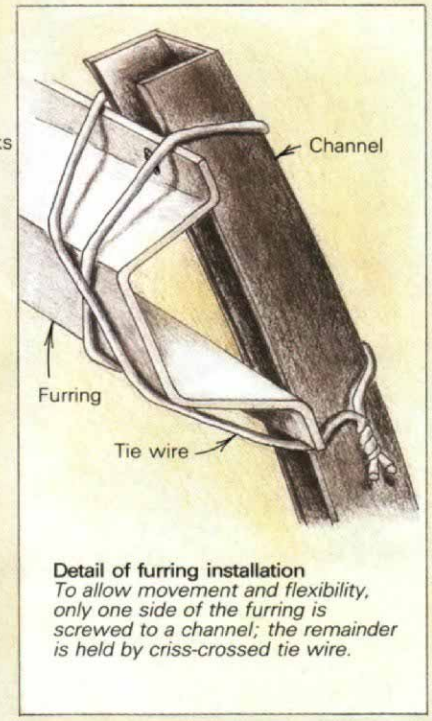
We vented the roof by drilling a series of 3-in. dia. vent holes, 18 in o. c. along the tops of all the I-beam webs. Then we installed three wind turbines on the roof and continuous soffit vents on the south side. Because there are no exterior soffits on the north side—where the addition joins the rest of the house—we added three eyebrow vents to the roof on that side. We insulated between the I-beams with 9-in. R-30 fiberglass batts.

Cold-rolled ribs and furring—Talking with a technical representative from the USG, I learned that to build a vault like this I could use 16-ga. cold-rolled steel channels for the ribs, bend them to the desired radius and then attach them to the structure. We decided to

Thirty-six-ft. long wood I-beams were supported by joist hangers on the end walls to create the barrel-vault shape. The curved blocking, run every 16 in., stabilizes the beams and provides a nailing surface for plywood sheathing.







use a U-shaped channel 1½ in. wide with ½-in. flanges, installed 24 in. o. c. Then we would screw and wire metal furring every 16 in. perpendicular to the ribs. The furring, made of 25-ga. galvanized steel, is hat-shaped in section.

To find out how to bend and install this system, I called the California Drywall/Lathing Apprenticeship and Training Trust in Hayward, California (23217 Kidder St., Hayward, Calif. 94545-1632). In conjunction with their training program, they have produced a series of film strips for training apprentices on all applications of drywall, plaster and lathing. They had two films on the sequence and installation of barrel vaults.

From the first film strip I learned that bending the U-channel and maintaining its structural integrity is critical. The channel should be bent with the flanges toward the inside of the vault. Since the flanges are in compression, the material can buckle and fail while being bent, thereby losing the smooth shape of the curve. The film strip showed a technique for bending the channel using a special bending device. It also demonstrated that you should screw only one side of the hat-shaped furring to the channel. Tie wire, crisscrossed and tightened, was used to secure the remainder of the furring (detail drawing above). This holds the furring flush with the cold-rolled channels, yet allows some movement and flexibility.

The second film strip showed the installation procedure for the gypsum board. A chart (taken from the *Gypsum Construction Handbook)* listed the minimum bending radii of dry-gypsum drywall by thickness. For our vault, two ¼-in. pieces of dry material could be used, or by moistening the back paper thoroughly prior to application, ½-in. gypsum board could be used. The moistening was necessary to allow the back paper and gypsum (in tension) and face paper and gypsum (in compression) to stretch and compress without failure. Of course, drywall screws had to be used to attach the gypsum board to the furring.

The axe-swing dance step—Now that I knew how the vault had to go together, I had to find the bending device. I called every rental place in the San Francisco Bay Area. No luck. Then, I called lathers and drywall contractors to find out if they would bend the cold-rolled channel. Again, no luck. Instead they wanted to bid the entire job. So, how could we bend the channel?

The solution to our problem slowly emerged. We built a full-size plywood template of the arch out of ½-in. plywood, with ½-in. plywood spacers underneath, and nailed it to the floor (drawing above). The U-channel fit over it with the bottom snug against the edge of the plywood. To hold the channel in place around the template, we nailed short 2x4s every 3 ft. around the outside of the arc, leaving enough room to drive wedges between them and the template. As the channel was bent around the template, we tapped a wedge into place. The length of the arc was just under 20 ft., and since the channel came in 20-ft. lengths, only one piece was needed per rib.

Unfortunately, the channel would straighten out whenever we removed the wedges. We tried dimpling the flange every 6 in. by hitting it with a cold chisel and a hammer. This took forever and didn't dimple the metal enough—it was hard on the template, too. We needed a faster way.

Dan happened to have an old axe in his tool box, and he decided to give it a try. By quickly hitting and denting the flange with the axe every 6 in., then turning the channel over and doing the same thing to the other side, we found that the channel would retain the shape of the arc of the template.

We had 20 ribs to bend, so we developed a rhythm for mass production. We called it the "axe-swing locomotion" dance. By rotating one's feet together from heel to toe and striking the flange with the ax, it was possible to develop a rhythmic pattern that created just the right swing motion to dent the flange uniformly. It took a great deal of hand/eye coordination and physical control on the swings to make it work, but agile dancers that we were, the job took no time at all.

The ribs were laid out at 2-ft. centers under the bottoms of the I-beams. The system was checked for roundness, plumb and parallel. The ends of each rib were securely anchored by screwing them to a metal stud run on top of the walls along both sides of the vault. At alternate I-beams, a ½-in. hole was drilled through the web, and the rib was tied to the I-beam with wire. The ribs were tied with a little slack in order to allow movement and to encourage the weight of the system to rest on the walls instead of hanging from the roof structure.

After the ribs were installed, we attached furring at 16 in. o. c. We continued with this procedure across the length of the roof, moving the scaffolding as necessary. Nine ft.

Inside the barrel vault, the drywall ceiling was screwed to a metal framework of arched ribs and straight furring hung from the bottom of the I-beams (above). Two layers of ¼-in. drywall were used to form the ceiling. The second layer was run perpendicular to the first. Residential drywall contractors shied away from the project, but a commercial crew that was between jobs happily took it on. They hung, taped and finished the job (below), including the barrel-vault ceiling, in three weeks.

Photo by Staff

from the end of each wall, at the top of the barrel vault, an electrical box was installed for ceiling fans.

Hanging the drywall—Finally, it was time to install the two layers of ¼-in. drywall on the barrel-vault ceiling. We ran the first layer parallel to the ribs (photo above) and the second layer perpendicular to the first. Soon after we started applying the drywall, our two laborers left the job to return to school. Because this was one of the least-pleasant tasks of the entire project, we decided it was time to call in a professional.

Most residential drywall installers weren't interested in working on the project because of the metal furring system, the ceiling height and the overall complexity of the project. However, we were lucky to find a commercial installer who needed to fill a gap in his work schedule to keep his crew employed. They hung, taped and textured the house in three weeks.

After they finished, we still had to cover the nuts and bolts where the straps held the haunch to the rafters. We found a local firm (San Francisco Victoriana, 2245 Palou Ave., San Francisco, Calif. 94124) that makes decorative trim plaster castings for Victorian houses and ordered 12 plaster keystones. They were hollow on the back and fit nicely over the exposed bolts (photo right).

It was hard to believe that the simple arc sketched on an exterior elevation 18 months before was now a three-dimensional reality. □

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