An Innovative, Panelized Roof System for Residential Construction

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In 1985, MIT founded the Innovative Housing Construction Technologies Program to explore ways to improve conventional wood-frame construction. Charged with identifying how existing materials and innovations could be exploited to improve building performance, speed construction, or reduce cost, the group focused on the roof as one aspect of construction that had grown increasingly complex (and so expensive), but which was usually uninhabitable because of the proliferation of roof trusses. In developing a panelized roof system, the primary goal was to create a single coherent scheme to serve the greatest possible range of applications. Emphasizing the cost-effectiveness of recovering the enclosed volume for habitation, and recognizing the need to accommodate a wide range of building types, the roof system supports hips and valleys and serves both as structure and insulated / ventilated envelope. As designed and constructed (for proof-of-concept and as part of the IBACoS Demonstration Project), the system consists of stressed-skin panels and a structural ridge beam, triangular in cross-section, and hollow. The ribbed panel is made entirely of 7/16 in thick oriented strand board (OSB), fastened with glue, and insulated with 8 in of high density fiberglass. Semi-circular holes are spaced evenly along the tops of the ribs, allowing cross-ventilation for roofs with hips and valleys. Because panels are insulated well and adequately ventilated, thermal performance is improved, and structural performance is comparable to similar-sized rafter and sheathing schemes. The hollow ridge beam supports panels during construction, but also provides both vertical and lateral load-carrying for the finished building. In conjunction with the functional design, the manufacturing process was carefully designed to provide credible evidence of the system's feasibility.

INTRODUCTION

For decades, the dream of the factory-made house has remained elusive. With roots in the earliest days of this century, architects and designers have long sought to create a building system based upon a kit of standard parts, but which would admit an infinite range of design outcomes (see, for example; Herbert, 1986). Except in the case of the fully assembled mobile home, the dream of the single-system or factory-built house has eluded us completely. Upon closer scrutiny, however, and admitting its reliance on site assembly, the present-day, wood-frame, house-building industry can be seen to be factory-based, employing a fully standardized (but flexible) system of supports, and with an infill of factory-made components: windows, cabinets, doors, and even stairs, to name a few. The result is a highly standardized and amazingly flexible system; a system that admits innovation in evolutionary increments.

In 1985, the Innovative Housing Construction Technologies Program (IHCTP) was formed at MIT. With support from a consortium of sponsors, the IHCTP set about to explore ways in which innovative manufacturing and construction technologies might be applied to improve the value and performance of single-family houses. After an overview of the state of the construction art, and with parallel projects in materials development, the group focused on the house roof as a place where innovation might best increase value. As new construction of houses has moved away from simple, small, ‘‘starter’’ homes to more complex, larger, trade-up homes, roofs have become significantly more complex, and so more costly. Further, with the increased-use of engineered-roof trusses, new houses often have large, enclosed roof volumes that are uninhabited and uninhabitable. Against this background, our goal was to add value to the roof system not just by increasing performance and reducing the cost, but to add substantially to the value of a house by recovering the enclosed volume for habitation. To this end, we developed a panelized roof system, using materials readily available (the project prototype was fabricated and erected in June, 1992), and based upon flexible manufacturing techniques. A complete recounting of this work is beyond the scope of this paper, and the interested reader is directed to the ***Forest Products Journal*** for a full account by the project team (Crowley, 1993). That paper explored all aspects of this project, including costs and manufacturing, while this paper confines itself to the current design, and with specific attention to the compromise between thermal and structural performance.

To create habitable space within the roof volume, the roof panels had to be designed to serve both as structure and envelope, and these dual and often competing requirements led to a series of difficult trade-offs and decisions. This report includes only cursory discussion of conventional frame construction, confined to touch upon some implications of panelization—those specifically relevant to a panelized roof—and to the design decisions made for the particular case of our proof-of-concept system. As our charge clearly included some proof of the more general concept of panelization, and not simply the development of an individual design scheme, this discussion attempts to carry a thread of continuity that ties the necessarily narrow decisions made here to the broader context in which they were made.

SYSTEM GOALS

Architecture

In designing a panelized roof system, our primary goal was to create a single coherent scheme that could be used in the greatest possible range of applications. Therefore, both functionally and aesthetically, independence from the house was among the primary design objectives. This independence implies that the roof system would support extensive architectural freedom—that is it should be functionally independent from the aesthetic design of the house, and therefore be compatible with the broadest possible range of building designs. Independence also implies that the roof system would be self sufficient structurally—an impossible goal at its simplest, but nevertheless mandating that the roof must carry loads as self-sufficiently as possible. The first goal was met by developing a system that can accommodate ridge lines, hips, valleys, shed roofs, dormers, and other penetrations. The second goal of structural independence is clearly impossible in its purest sense—the house holds the roof up, and both gravity and transverse loads must be carried from the roof to the ground through the house. Nevertheless, as an approach to meeting this second goal, we hoped to design the system so that a roof could sit on a frozen pond—the wind could blow it around, but that under gravity loads, only vertical support would be required. Throughout its development, the roof system was designed to create habitable space within the roof volume; whether this space would be used for storage, would be developed into rooms under the sloping roof, or would simply form a sloping ceiling over rooms below.

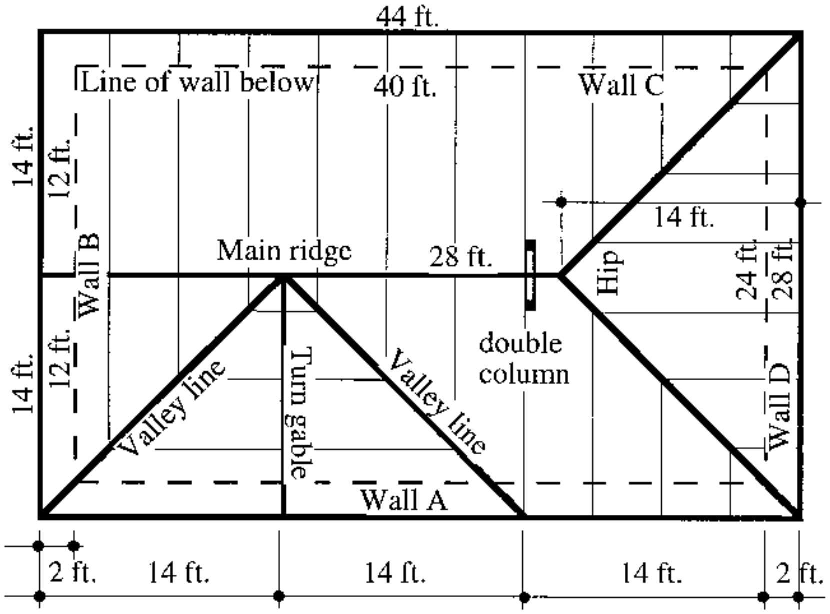
Functionality

The roof forms the primary defense against the elements - wind, water, and snow. Further, to support habitability, the roof system must be insulated, and the enclosed volumes must be shaped appropriately for occupancy. The first of these requirements is met by structure and finishing: structurally, wind and snow loads must be carried into the house below. Against the elements, the roof system was designed to accept conventional roof coverings, including metal and other sheet products. The requirement for insulation might be met in a variety of ways, and these are explored further below. In one instance, panels might have insulation laminated between two faces; common with so-called structural-insulated-panels, and in which the insulation is expected to play a structural role. Alternatively, panels might be more conventionally constructed and insulated, with structural ribs, and compartmentalized insulation. To create habitable spaces within the roof volume, either the roof form must be pitched steeply enough to create these spaces above an implied attic-floor plane, or the roof system might simply be placed over open rooms below; thereby creating taller, sloped ceilings. In the interests of broadest possible application, the system was optimally designed for the range of roof-slopes around 10:12, but is adaptable to slopes down to 7:12. Finally, the roof system must be easy to assemble. To this end, and to play a primary structural role as well, a ridge beam was designed to support the roof panels both during construction and after. This ridge serves to carry both vertical and lateral-forces, and was designed to serve as a utility chase as well. Figure 1 shows the system employed in the proof-of-concept house.

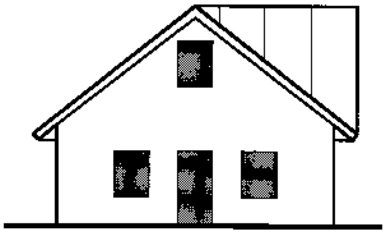
Thermal Issues

The thermal requirements of the roof system lie primarily in achieving an acceptable R-value, avoiding thermal bridging, and preventing air-infiltration wherever possible. In developing our panel, we first considered the range of existing, so-called, structural-insulated-panels. Typically, these are comprised of two faces, (often both made of OSB), with a layer of rigid foam insulation between. The most common choices for the core material are plastics; polystyrene, (both expanded and extruded), as well as polyurethane. For this whole class of insulations, the R value per unit thickness is 5 or more, and so, adequate levels of insulation are readily achieved even with only modest panel thickness. In a sandwich panel, the foam insulation is not usually vented, and so when used for a roof, a panel's top face can get very hot unless special measures are taken. Indeed, for some regions, roof-covering manufacturers will not warrant their products when they are placed over unventilated, rigid-insulation panels. In addition to concerns over the temperature of the roof covering, the structural performance of the foam core may be compromised by this heat as well. To reduce the skin temperature of the upper panel face, we felt the need to use or develop ventilated panels, and this in turn led us away from foam-core panels. In the end, for both structural reasons **and** thermal-performance, we designed a system based upon ribbed panels (Fig's. 2, 3, 4, 5). Based upon most building-code standards, we settled upon an overall roof performance of R-30 (hour—ft.^{2} – F/BTU) as a reasonable goal, recognizing that our system can be changed easily to improve insulation performance.

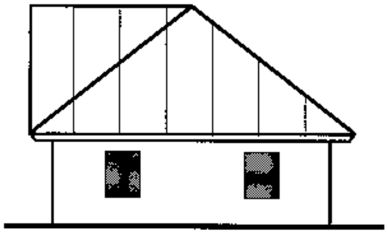
Figure 1. *Proof-of-Concept House: Roof Plan, Elevations, and Building Sections*



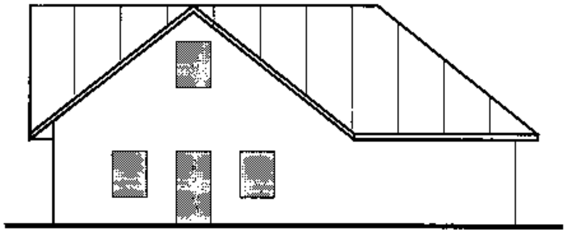
Roof Plan



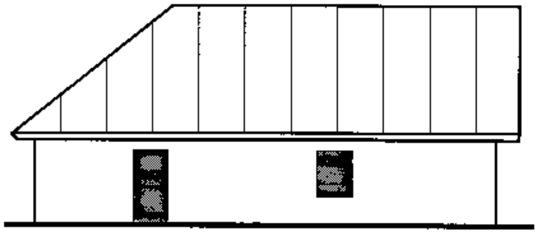
Elevation of Wall B



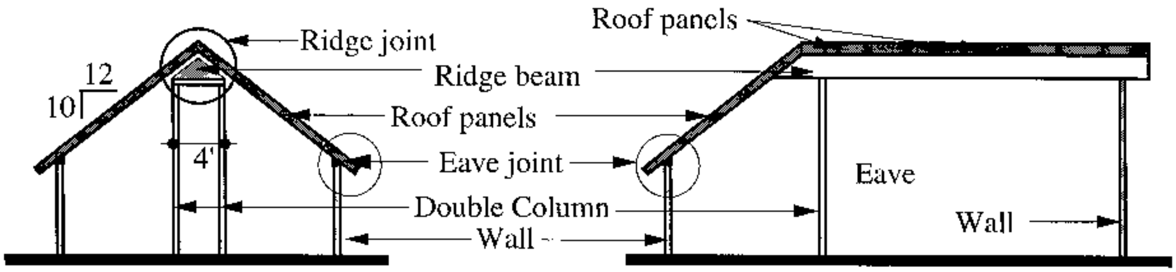
Elevation of Wall D



Elevation of Wall A

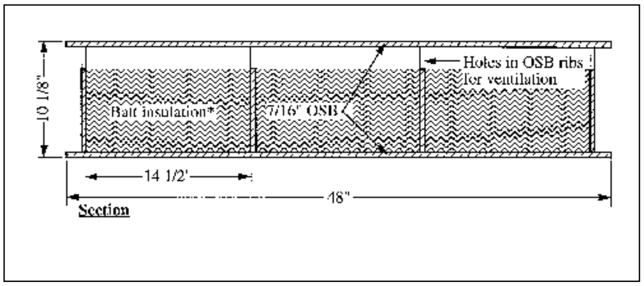


Elevation of Wall C



Cross-section **Longitudinal section**

Figure 2. *Cross-Section of Typical 4-foot-wide Ribbed Roof Panel*



The need for competent joints pervades any system of panelized building. Thermal performance of insulated panels is excellent over the panels themselves, and the field-made joints become the thermal weak point. Construction errors promote air infiltration and gaps in the insulation at joints. Standard practice for making panel-to-panel joints for rigid-foam-core panels often includes OSB splines—to promote structural continuity across panels, and to minimize air infiltration—and may include field-placed (usually expanding) foam sealant as well. Our panel-to-panel joints employed a special spline made of OSB faces, a partial rigid-foam core, and blocks of compressible foam (Fig. 3). At the ridge line, panels were intentionally held back to create a narrow gap for a ridge vent, but also to allow final placement of insulation to fill the space between panels (Fig. 4). As the panels are registered along the ridge beam (top-registered), this gap is controlled to be 2 inches wide. At the eaves, the panels may either end at the outer-wall plane or project beyond it. In either case, the panel insulation extends (within the panel) to an eave-level block to maintain a thorough envelope, to conserve insulation, and to support a range of eave-finishing details (Fig. 5).

Structural Issues

Full discussion of conventional wood-frame construction or even those aspects specifically related to panelization is beyond the scope of this paper. The interested reader is directed to a recent paper by the author that provides an overview of panelization, and its implications for structural design (Morse-Fortier, 1995). What follows here is a cursory overview of how we came to our present system design.

Figure 3. *Cross-Section of Roof Panels at Panel-to-Panel Joint*

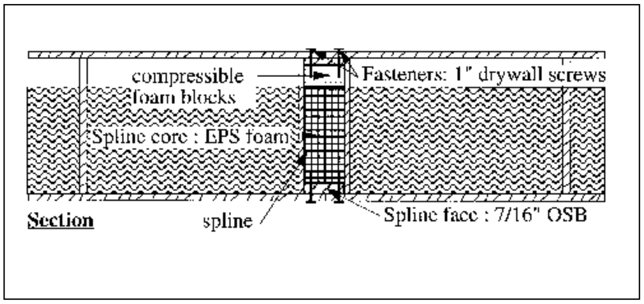


Figure 4. *Cross-Section of Roof Panels at the Ventilated Ridge Joint*

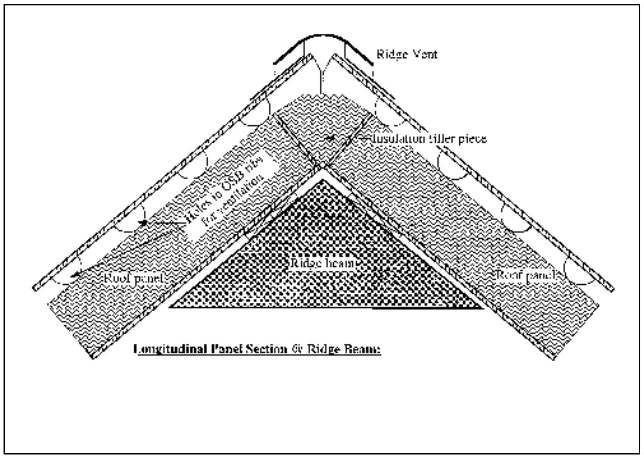
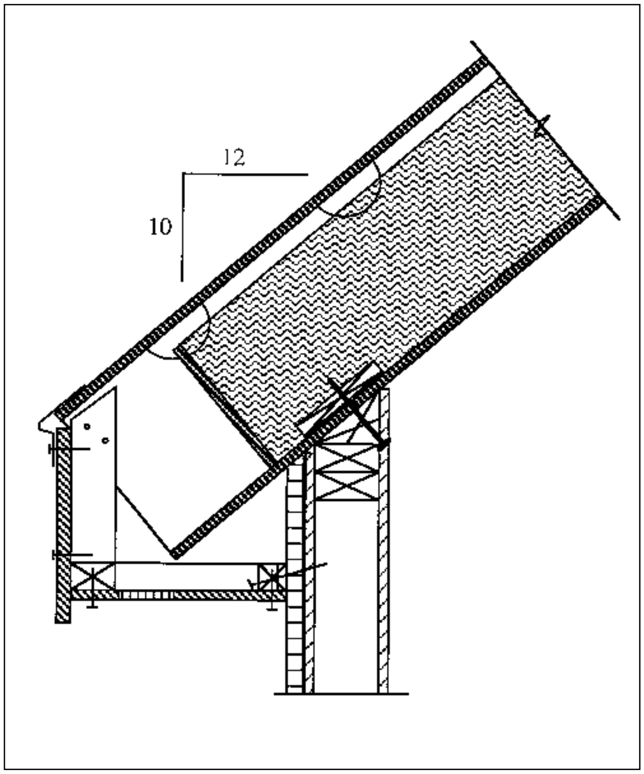


Figure 5. *Example Eave Detail (© 1992 by Jordan Dentz)*



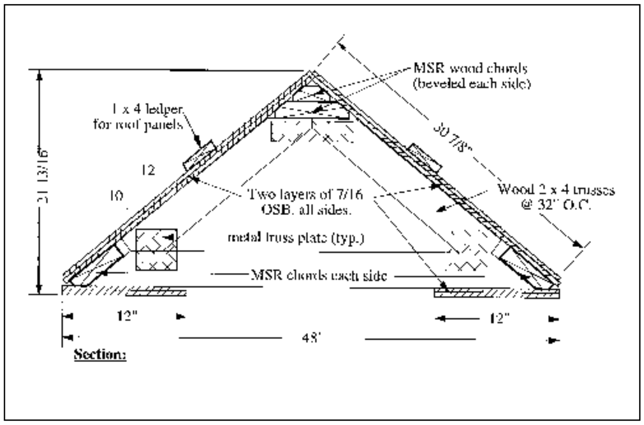
As stated above, our goal was to create a roof system that would be as independent as practicable from the construction of the house beneath. One way to imagine a panelized roof system is to consider a fully constructed conventional roof, separated into manageable parts, and re-assembled into a whole. Imagined thus, panels could be made and assembled to behave like small 'sub-collections' of rafters, or alternatively, they could be joined to create large coherent plates or diaphragms. In this latter case, the requirements of the component panels would vary with each house, and any standard panel would have to be capable of withstanding loads anticipated in the worst case. Strategically, either a standard panel would be designed to some reasonable standard—thereby limiting the range of houses that could be built, or it would be designed to some extreme standard - thereby providing unnecessary conservatism most of the time, and variable risk all of the time. For our roof system, we designed the panels to act for the most part independently of one another. We adopted a ridge beam to carry vertical loads and even more uniquely to resist lateral forces as well (Fig. 6). The following paragraphs provide explanations of how we reached our decisions. As stated in the introduction, a range of choices exists, and in explaining how we made ours, others may be discernible as well.

SYSTEM DESIGN

Thermal Design

Based upon consideration of most local building codes, we settled on a target thermal resistance of R-30 (hour—ft.^{2} − F/BTU) for the roof system overall. This was achieved with 8 inches of high-density fiberglass insulation, housed within a nominal 10 inch deep panel (Fig. 2). This R value can be increased by changing the insulation, or by including more of the same insulation in a deeper panel. To provide ventilation along the panel length as well as across (for hips and valleys), panel ribs have half-circular holes located periodically along their length. These holes help reduce thermal bridging through the already-thin ribs, and balance stresses within the panel faces to better exploit the structural properties of OSB. Panels are joined along their edges with flexible thermal splines (Fig. 3), and along the ridge line a space is left to provide final placement of a narrow insulating strip, and to accommodate the ridge vent (Fig. 4).

Figure 6. *Cross-Section of Ridge Beam*



System Structural Design

In terms of the end objective of overall structural stiffness, the best strategy for structural design of single family housing lies in developing the diaphragm potential of the walls, floor, and roof surfaces and fastening them together to create a rigid ''box.'' Applied to panelized construction, this approach implies fastening panels together to create large stiff plates or diaphragms. In fact, however, such a strategy places significant reliance on the panel-to panel connection, which in turn emphasizes the field assembly of the system. Ironically, the overall system quality would rely upon quality control in the field, when in fact much of the point of panelization in the first place derived from the desire to better exploit the quality control possible in a factory. Consequently, in our system, the discrete elements retain their individuality in the final overall structural scheme.

To make habitable space beneath the rafters, internal structural elements (such as collar ties) must be avoided. Further, to be as nearly independent of the house as possible, neither can a roof system rely upon the presence of a second floor to form a tie. For example, the roof system may be enclosing a room with a sloping ceiling, or it may be creating habitable space by resting upon a knee wall. Considering the difficulties posed by collar ties, the risk of depending upon a floor level tie, and considering the above mentioned difficulties of assembling panels into diaphragms, our system employs a substantial ridge beam, and ribbed panels.

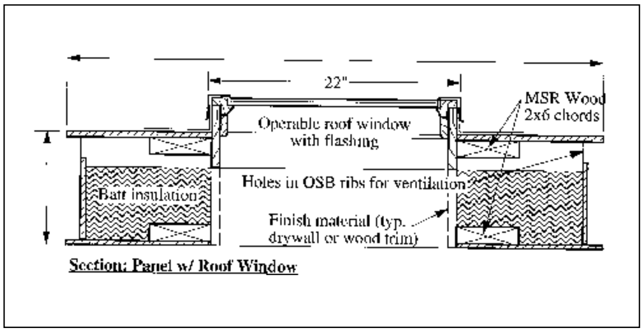
The following points summarize the load carrying strategy of the panelized roof system for both vertical (gravity) loads and lateral loads:

● Gravity Loads

- Panels transfer self-weight and snow load through one-way bending along the traditional rafter lines from ridge to eave. For hips and valleys as well, this remains the primary load carrying strategy, but with structural ties running along hip and valley lines, additional axial stresses are developed in the panel faces as well. Hip and valley roof-planes behave as point and edge-supported folded plates. Where roof-windows and skylights force partial removal of the panel skins, internal framing carries loads around these openings (Fig. 7).

- The ridge beam carries vertical loads to gable ends and/or supporting walls or posts. The need for intermediate supports depends upon house width (panel span), roof slope, snow load, house length (ridge span), and the

Figure 7. *Cross-Section of Panel @ Roof Window, With MSR Structural Reinforcement*



presence (or not) of hips (Fig. 1). The ridge beam is capable of acting as either a simply supported, cantilevered, or multiple span beam.

- The gable ends and any intermediate posts must be detailed to transfer the potentially substantial gravity loads from the ridge. In the case of long slender posts, this may require special bracing against column buckling.

• Lateral Loads

- In the across-house direction, panels transfer wind and earthquake loads directly into the ridge beam. Although the panels are connected across their lines of intersection through splines, the overall roof does not transfer load through diaphragm action in any appreciable amount. This is ensured by the relative flexibility of the spline connections as compared against the substantial lateral stiffness of the ridge beam. It is important to note, however, that this strategy requires lateral support of the ridge beam—thereby dictating a structural attribute of the house (see next item).

- The ridge beam transfers across-house loads into the gable ends, where present, and/or into interior walls in the case of a hipped roof or an intermediate support. In designing a house to accompany this roof system, these walls must be designed to withstand the wind and/or earthquake induced shear loads. This is doubly important for a hipped roof where the end sections of roof will be somewhat stiff, but were not designed to resist these loads. This reliance on shear walls is an admitted but necessary departure from the ideal of designing a roof system to be fully independent of the house below. In the special case of a hipped roof, the shear walls might simply be considered as part of the roof structure, delivering their load to the eave plane.

- In the along-house direction, panels act both as individual rectangular diaphragms—transferring loads into the house side walls, and as an overall diaphragm. Here, because they are fastened along their splines, diaphragm action develops naturally, and without the lateral stiffness of the ridge, this action constitutes a stiff load path. In this direction, however, the diaphragm action is a function only of the individual panel length and the load, (a case usually governed by earthquake accelerations). As the individual spline lines each experience the same shear stress, the panel connection (fastener schedule) can be designed to withstand this single specific shear load, and the design remains independent of the overall building / ridge length.

- As an example of lingering complexity, the hip ends may also develop stiffness through diaphragm action and thereby act to transfer along-house loads into the side walls of the house. In general, this load path is assumed to be secondary, and as no special provisions are made to stiffen these spline connections beyond the requirements above, care must be taken to provide adequate shear stiffness in the supporting walls.

Structural Design; The Composite Ridge Beam and its Attributes

The final design for the ridge beam is comprised of a reinforced triangular-section box beam with performance attributes that go well beyond those implied by its name alone. For the proof-of-concept house, with its 10:12 pitch, the ridge-beam cross section was 48 in wide by 22 in deep, was made principally of OSB and trusses, and was reinforced with Parallam® chords. To meet the same structural objectives with a more-standard material, these Parallam elements were replaced by machine-stress-rated lumber (MSR) for the IBACoS Prototype (Fig. 6). These chords run axially along the full length of the beam, two layers of $\frac{7}{16}$ in OSB are applied to the sides and part way across the bottom, and the beam is built around a frame of trusses, each comprised of 2x4 chords fastened with Mitek® plates. Phenol-resorcinol-formaldehyde (PRF) glue was used throughout the manufacture, and in the prototypes, the bottom sheets of OSB were fastened to the chords with screws as well. The ridge beam serves a variety of functions, and its design reflects this variety in a number of its features. These functions and features are summarized as follows:

- The ridge beam is used as the first element of the roof assembly. Continuous ‘‘ledger pieces’’ provide top registration for each panel, and support each panel until it is fastened.

- The ridge beam is 48 in wide. This width provides enough transverse stiffness to allow the roof to be assembled one side at a time, (although for a very long ridge line, some care may be required to prevent torsion and its resulting distortion). In the finished structure, the ridge serves to transfer wind and earthquake loads from the roof panels to shear walls below—thereby helping to rationalize the lateral-load carrying strategy for the house overall.

- The MSR (or Parallam®) chords run along the ridge at the top and in the lower corners of the triangular cross-section and these constitute the major axial stress carrying elements—akin to flanges in a wide flange beam. Their location allows supporting posts to be placed under the lower corners of the cross section, thereby freeing up the space below the centerline of the ridge. For the proof-of-concept house (and wherever the beam is 48 in wide), these posts are separated by the width of a door or window (Fig. 1).

- Because of its stiffness, few intermediate supports are required along the length of the ridge beam. As an example, for the extreme case of a 40 ft wide house, with a 10⁄12 pitch, and under a 40 psf design snow load, the maximum simple span for the ridge beam is 25 ft, (a value governed by deflection criteria).

- The ridge beam is hollow, and its central cavity can be used to run building services—wiring, ductwork, and even sprinklers.

Overall, the design of the ridge beam stands out as an innovation that could be incorporated in a wide variety of roof systems. While it was designed to accommodate and function with the ribbed panels of this system, its design is effectively independent of the panel design: it could be used with different roof panels, or even as a service chase and support for conventional rafter framing.

Structural Design; The Composite Panel and its Attributes

Considering the prevalence of rigid-foam-core panels in the current marketplace, it seems only fair to justify our decision to develop a ribbed panel instead of simply including one or another extant panel. Our primary reasons were structural. In bending, all stressed-skin panels develop tension and compression in the bottom and top faces respectively, with the internal material resisting shear. Under this shear, polymer-based foams are somewhat flexible, and over time, these core materials will creep. Where the lack of ventilation raises the top-skin temperature, the polymer core becomes even more susceptible to creep. As mentioned above, to increase panel stiffness, foam-core panels are often made deeper than justified on thermal grounds alone, leading to increased expense for the core, but still not necessarily meeting the structural requirements of longer spans. Taken together with our concerns for ventilating the roof system, these attributes led us away from foam-core panels. By using thin OSB ribs, panel stiffness is increased markedly, with very little thermal penalty. By separating the functions of shear-transfer and insulation, our panel design can accommodate a wide range of insulations, even blocks of rigid foam.

As designed and built for both the proof-of-concept and as part of the IBACoS Demonstration Project, the ribbed panel is made entirely of OSB, fastened with PRF glue, and insulated with 8 in, high-density fiberglass batts (Fig. 2). To be compatible with conventional framing sizes, the ribs are 9-¼ in (corresponding to a nominal 2x10), and so the overall panel depth is 10-⅛ in. For longer spans and/or higher loads, a nominal 12 in panel is possible as well (11-¼ in. rib width, and overall 12-⅛ in. depth). Further, to promote compatibility with conventional insulation widths, ribs are placed at 15″ o.c. (Fig. 2). To permit cross-ventilation, the ribs were manufactured with semi-circular holes cut along their upper edge (visible in Fig. 4). While critically important to cross-ventilating, these holes obviously have implications as well for the structural attributes of the panel. Surprisingly, in its material attributes, OSB shows a capacity to endure higher compressive than tensile stresses axially. The removal of material for the ventilation holes shifts the centroid of the panel section downward, lowering tensile stress and increasing compressive stress for any bending moment. In the end, the ventilation holes were included with no perceptible increase in bending-induced tensile stress—the strength governing criterion. Conceptually, the ribbed panel functions as if it were a collection of engineered I-joists, with wider-than-usual flanges, and fastened along their edges. By varying the thickness of the OSB ribs and faces, or by changing the number of ribs, the structural attributes of the panels can be adjusted to differing performance levels.

In considering panel structural performance, deflection criteria most often governs design, and so a look at maximum allowable spans provides a reasonable basis for comparing panels to rafter systems. Table 1 provides this comparison.

CONCLUSION

MIT's Innovative Housing Construction Technology Program has developed a complete roof enclosure system. Based upon existing materials and simple structural concepts, the roof system incorporates stressed-skin panels and a structural ridge beam to provide structure and enclosure. By eliminating structural members from within the enclosed space, and based upon a significant level of structural independence, the system supports direct habitation of the roof volume, either as living space, or as open space above rooms below. Roof panels are capable of spans that equal or exceed those of comparably sized rafters. The ridge beam provides vertical and horizontal support to the panels both during construction

***Table 1.** Maximum Allowable Spans*: Comparison of Panels and Rafters*

Nominal Depth:	OSB Thickness:	Ribs:	Maximum Allowable Span:	Rafter configuration:	Maximum Allowable Span:
10 [inches]	7⁄16 [in.]	4	16.42 [ft.]	2×10 @ 24″ o.c.	14.30 [ft.]
10	5⁄8	3	17.97	2×10 @ 16″ o.c.	16.38
10	5⁄8	4	18.25	2×10 @ 12″ o.c.	17.95
12	7⁄16	4	18.98	2×12 @ 24″ o.c.	17.33
12	5⁄8	3	20.37	2×12 @ 16″ o.c.	19.82
12	5⁄8	4	20.70	2×12 @ 12″ o.c.	21.87

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*Spans are for a 4 ft.-wide panel or strip of raftered roof, under a 40 psf uniform load.

and afterward—thereby simplifying installation, and rationalizing the lateral-load carrying strategy for the entire building.

In its final design, the roof panels have an overall R-value of 30 for the nominal 10 inch panel, and R-38 for a 12 in.-deep panel. With a vented ridge line, and with panels that accommodate cross ventilation, the roof system provides competent thermal enclosure for a wide range of architectural designs.

ACKNOWLEDGMENTS

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