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Innovative Materials and Construction Systems for Energy-Efficient Building Envelopes

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ABSTRACT

Energy efficiency, by itself, is not always a priority of home builders or buyers. The most realistic approach to develop new technology for energy-efficient and affordable housing is to pursue these goals within a comprehensive program of innovative construction for buildings. A research program under way at a U.S. university involves key groups with expertise in materials, manufacturing, thermal performance, structural design, and architecture. Several new concepts for manufactured components for building envelopes are under investigation. Low-density foamed concrete has been developed to be used as the core of sandwich panels; the foam serves both insulating and load-bearing functions. Another concept is based upon roof panels that use oriented strandboard (OSB) as both the ribs and faces of a three-dimensional structure. The structural and thermal properties of the panel have been investigated and a full-scale roof demonstration using these panels has been assembled. More advanced concepts under investigation include vacuum insulation elements.

This paper summarizes the properties of the foam and the OSB panels and describes the results of a full-scale demonstration using the panels for a complex roof geometry.

INTRODUCTION

Energy efficiency, by itself, is not generally a priority of home builders or buyers. The most realistic approach to develop new technology for energy-efficient and affordable housing is to pursue these goals within a comprehensive program of innovative construction for buildings. Research must be guided by the constraints and opportunities imposed by the structure of the housing industry. This approach examines industry structure, distribution channels, service, investment potential, and market demands. To be successful, a new building product must achieve a clearly established benchmark of performance throughout the process of design, manufacturing, transportation, site assembly, and in-service performance.

The technology of materials and manufacturing has advanced considerably in the past 20 years, but application of these advances to building systems for housing has lagged. In applying advanced technology to housing, we have chosen to follow the trend in U.S. residential construction toward the use of building components fabricated off site, known as componentization. Successful components are accepted because they add value to a house more efficiently than the builder can do it on site and are compatible with the American 2 × 4 platform frame construction system. Although generally conservative, builders specify new components because they bring them better quality, lower costs, fewer delays, and less variation, resulting in fewer "callbacks" and more satisfied customers. The overall effect of componentization is to simplify the fabrication and assembly requirements on the job site. It makes sense as a strategy because of the continuing decline in availability of skilled construction workers, the increase in scattered-site developments, the rising cost of traditional building materials, and the ease with which components can be produced, distributed, and integrated with 2 × 4 platform construction. Higher value and more complete components and subsystems represent an effective strategy to reduce the cost and increase the quality of housing.

The project objective was to identify, define, design, and test potentially viable house components using innovative combinations of materials, design, manufacturing, and distribution techniques. This research has been wholly funded by a consortium of industrial sponsors. In addition, an advisory board of builders, designers, and representatives of model code agencies has met frequently to review the program. For the past three years, we have focused on the development of a component system for roofs of single-family detached and attached houses. The research has included design, prototype manufacture, and proof-of-concept test of an innovative ribbed panel that makes up a net-shaped roof system. This includes consideration of improved thermal performance, structural analysis, and long-term deflection testing.

A parallel research effort in the consortium was the development of new materials that could form the basis of the next generation of building components. In particular, low-density foamed cement was identified as a promising material to serve as the core of sandwich panels. The goal was the development of a foam that has good structural and thermal properties so that it can simultaneously serve as a structural member as well as a thermal insulation.

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This paper will present an overview of the progress to date in this research program.

THE NET-SHAPED ROOF SYSTEM

The net-shaped roof system has been developed as an economical, value-added method of providing a complete roof enclosure. The roof system has been designed for flexibility, efficient use of materials and labor, and superior performance at an installed cost, which yields a better value than conventional rafter-and-truss construction techniques. The roof system is composed of five elements: design software, support beams, structural insulated panels, the joining system, and the manufacturing process. A stressed-skin, ribbed panel was chosen because it allowed the use of commodity materials that are most cost-efficient for their applications. Oriented strandboard was selected as the primary structural material for the roof panels for its good physical properties and its availability in large sizes and because it is produced from low-value, commonly available wood fiber. The panel may be insulated with fiberglass or other low-cost insulation. This design easily accommodates thicker roof panels for higher R-values than conventional rafter construction.

The roof possesses the most complex geometrical challenges and structural and thermal requirements and is consequently the most difficult part of the house to frame conventionally. It is also the final and most crucial step on the critical path to getting the house weathertight, and, therefore, increasing its speed of construction is greatly beneficial. These conditions indicate a great potential for improvement over conventional construction. Further, the roof system is compatible with commonly available wall panel and engineered floor systems. The rib construction also allows through-venting of the insulation space, even at valleys and other complex joints.

The Roof System

The net-shaped roof system is easy and quick to design, manufacture, and erect. It uses composite panel materials and structural adhesive to achieve a degree of performance and a structural capability equivalent to or better than conventional construction. Thermal performance is improved over rafter construction by reducing bridging and other thermal defects.

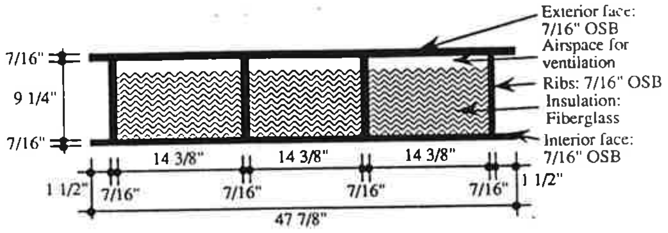
Because of the links developed between a user-friendly order entry and graphic design environment and production system, roofs will be custom manufactured to specific customer requirements. The production machinery enables panel, ridge, and joining components to be manufactured on a semi-automatic assembly line.

The net-shaped roof system can be installed on the walls of an average-size two-story house or townhouse structure with the aid of a small crane in approximately three to four hours. An important attribute from the view of homeowner and builder is complete freedom of use of the roof cavity volume for additional living or storage space, with minimal structural encumbrances.

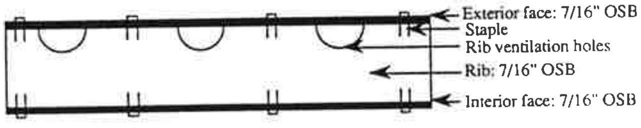
Enclosure Component

The enclosure components (or panels) span from ridge to eave (or other, such as hip, valley, etc.) without intermediate support. They are of standard width (4 feet) but range in length up to 24 feet. Panels may have two rectangular ends or one or both of the ends may be angular in the case of a valley or a hip roof.

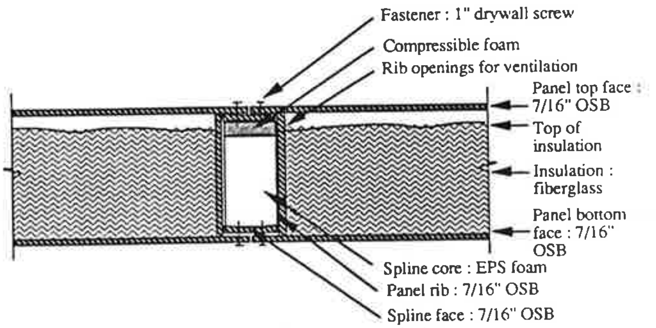
The basic component (Figure 1) consists of an inner and an outer face and four ribs running lengthwise between faces. Both the faces and the ribs utilize oriented strandboard. Fiberglass or mineral wool insulation is placed inside the component to within approximately one inch of the inside of the top face. The space remaining above the insulation serves to ventilate of the roof panels. This is important for elimination of water vapor, longevity of the roofing material, and prevention of frost lines. To permit air to pass across ribs and allow ventilation of hips and valleys, the tops of the ribs are notched. Semi-circular holes, four inches in diameter, are cut out of the rib tops at 12 inches on center. These holes were included with no loss in panel strength and a small reduction in stiffness. In addition, the advantage of their semicircular shape derives



Panel cross section



Rib notching for 2-way ventilation, panel longitudinal section



Spline panel-to-panel joint

Figure 1 *Panel cross section, rib notching for two-way ventilation, panel longitudinal section, spline panel-to-panel joint.*

from the manufacturing convenience of cutting (or punching) circular holes along a cut line but extends as well to reducing stress concentration around the holes. The rib-face connection is made by a glue bond with a phenolic resin. Staples, inserted with a pneumatic stapler through the face into the rib edges, provide a mechanical fastener to aid in glue surface contact and to facilitate the handling of the components before the glue has set.

The enclosure component may be made in varying depths ranging from 10⅛ inches and up. Increasing the depth enables more insulation to be placed within and increases the span capability of the structure.

Ridge Beam

The use of a ridge beam eliminates the transformation of vertical loads into horizontal thrust at the walls. With a ridge beam in place, each panel can be dealt with as structurally independent for purposes of erection and primary load carrying. Additionally, the ridge beam enables the house to have an unobstructed roof cavity space.

The ridge beam (Figure 2) is a triangular-shaped, reinforced box beam whose angles conform to the slope of the roof it is supporting. The ridge beam gets its shape from a series of small triangular wood trusses. The two sloping sides of the beam and part of the bottom are wrapped with sheathing. Also, engineered wood sections are placed in the three corners of the beam (cornerwood). The sheathing acts as the shear web of the beam, and the cornerwood performs as the flange.

Due to its triangular form, the ridge beam is wider than it is deep. It is therefore very stiff laterally as well as vertically. This has important structural benefits in the design of the house. The space within the beam may be used to carry electrical, HVAC, sprinklers, and other services as well.

Erection of the Roof Components

Erection of a 1,700-square-foot roof system can be comfortably accomplished with a crew of four, plus a small crane and operator, in three to four hours. A crane lifts and places the enclosure components on the ridge beam and the wall of the house. The components are moved into position at an angle equivalent to the slope of the roof with the aid of special crane rigging hardware.

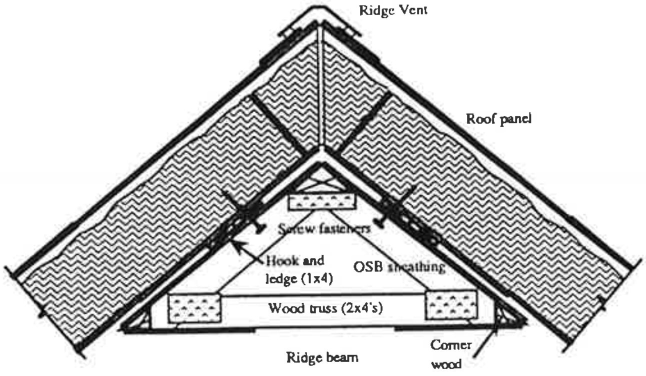


Figure 2 Ridge detail.

Enclosure components are set and fastened with between four and six fasteners. The spline connectors and associated fasteners are installed after all of the components have been set and the crane has left the site. The enclosure components have a weatherable coating on the exterior surface, enabling them to remain exposed for one to three months. Traditional roofing materials are installed over the roof components at the builder's convenience. Roofing is no longer a critical path test.

THE PROOF-OF-CONCEPT STRUCTURE

A full-scale proof-of-concept structure was built in June 1991 utilizing the net-shaped component roof system. The purpose of the investigation was to further develop manufacturing techniques, connection concepts, and assembly procedures and to verify some aspects of the structural performance. The proof-of-concept structure is 44 feet long, 28 feet wide, and incorporates a straight gable, turn gable, hip, and dormer. The roof slope is 10 in 12 (approximately 40 degrees, as shown in Figures 3 and 4).

The panels for the proof-of-concept structure are 10⅛ inches thick overall and utilize 7/16-inch oriented strandboard (OSB). The 9¼-inch interior depth makes them compatible with 2 × 10 framing. Fiberglass batts, 8 inches thick and rated at R-30, are used.

There are two ridge beams, both 22 inches deep and 48 inches wide. The secondary beam spans 12 feet. The main beam spans 26 feet and supports the secondary beam 12 feet from one end. The beams are sheathed with two layers of 7/16-inch OSB. A parallel strand engineered wood product is used in the corners of the beam to carry tensile and compressive forces.

Results of Proof-of-Concept Structure

The proof-of-concept structure was assembled and disassembled a number of times. A speed of approximately

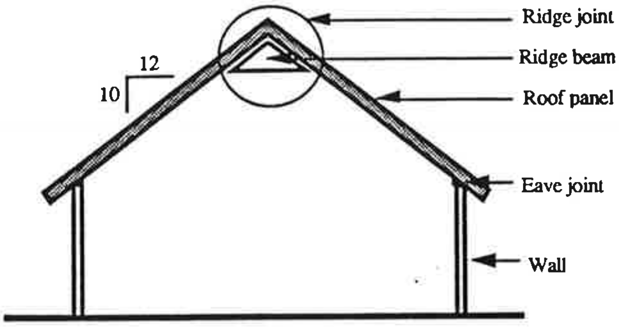


Figure 3 Cross section of proof-of-concept structure.

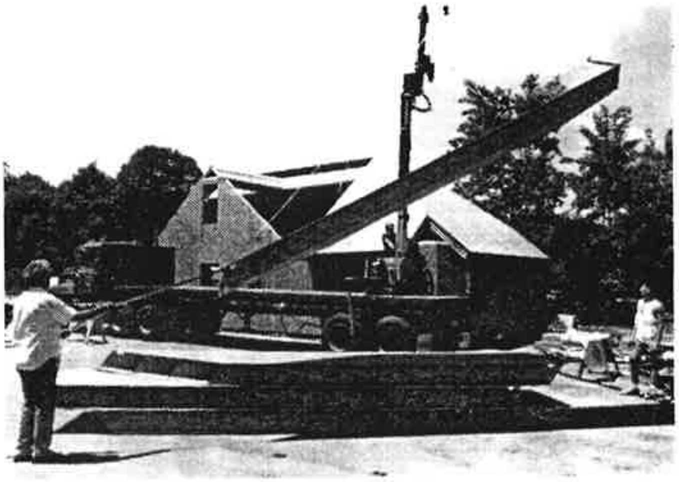


Figure 4 *Roof components being installed on the proof-of-concept structure.*

five minutes per panel was achieved, implying that all of the roof panels could be assembled in 2½ hours of crane time. The various features to aid the assembly process worked well. This includes a "hook and ledger" arrangement on the panels and ridge beam to accurately register the panels on the roof. Alternative joint designs were experimented with in the hip, valley, and spline joints. The improved hip and valley joints enabled the panels to be placed more accurately and to form a tighter seam. Work continues on various types of splines, with the goal being a spline that is inexpensive, easily manufactured and installed, and thermally efficient. By use of a structural system whereby the panel-to-panel connection does not carry substantial loads, flexible joints can be used. A spline made with compressible foam, which can be installed easily, appears as an attractive option. We worked out many small but important bugs relating to the detailed panel design, site assembly sequence, and lifting and fastening of panels.

The structure has now been standing for nine months, has survived two major storms, and remains unscathed after a New England winter. The most important results of the proof-of-concept structure were the invaluable experiences in handling and assembling roof components of this type and the knowledge that it could be done.

THERMAL PERFORMANCE OF THE NET-SHAPED ROOF SYSTEM

The overall R-value of the panel has been calculated at approximately 31 $ft^2 \cdot °F \cdot h/B$. This value takes into account conduction and convection through the insulation, the OSB faces and ribs, and the airspace and surface air films. It is based on a one-dimensional analysis and considers two-dimensional fin effects of the rib (which turned out to be negligible). The R-value of the insulation used was 3.2 $ft^3 \cdot °F \cdot h/B$ per inch of thickness. In two cases, interior and exterior air temperatures were set at 70°F and 0°F, respectively. In the first case, the airspeed in the venting space was assumed to be negligible. In the second case, the R-value of the panel was calculated with an extreme airspeed of 40 ft/sec through the ventilation air space. This resulted in an R-value of 29.2, only 6% lower. For rafter construction of the same dimensions, the same calculation yields an R-value of 27 ($ft^2 \cdot °F \cdot h/B$) for the case of negligible airspeed (88% of the value of the rib panel). The rafter calculation assumes a perfect quality of construction, even though defects in the thermal envelope may often be present in the field-fabricated system.

It is a simple matter to further increase the thickness, and hence R-value, of the enclosure component. By increasing the interior depth of the roof panel to 11¼ inches (the depth of 2 × 12 framing), we add two additional inches of insulation, bringing the R-value up to approximately 37.5 ($ft^2 \cdot °F \cdot h/B$). The materials cost of the deeper version is less than 8% higher than the nominal 10-inch version, and there is only a negligible increase in manufacturing cost. Increasing the insulation in a conventionally framed roof system is more complicated because there is a substantial cost penalty associated with old-growth timber needed for deeper rafters. Alternatives require additional steps in the field and/or higher-cost insulation materials, such as polyurethane foams.

Use of the net-shaped roof system should result in tighter roof construction. That is, air infiltration should be reduced from conventional construction due to the fewer seams and tighter joints present in the system. Site-assembled roof systems have a propensity for construction defects, such as insulation gaps, blocked ventilation passages, and thermal bridges. The manufacturing environment in which the net-shaped roof components are built provides the opportunity to control and thereby minimize these defects.

STRUCTURAL SYSTEMS OVERVIEW

In developing this net-shaped roof system, our primary goal was to create a single coherent scheme that would be used in the greatest possible range of applications. Therefore, both functionally and aesthetically, independence from the "house below" has been a design objective. 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.

The first goal was met by developing a system that can accommodate ridge lines, hips, valleys, shed roofs, flat 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 under gravity loads, only vertical support would be required.

Much of what is unique about this system is made clearer by first discussing conventional frame construction, by outlining some overall implications of panelization (those specifically relevant to a panelized roof), and, finally, by summarizing the design decisions made for the particular case of the proof-of-concept system. The intent is to indicate the thread of continuity that ties the necessarily narrow decisions made here to the broader context in which they were made.

In describing how various conventional roof structures work, we can focus first on how vertical loads are carried in several cases of two rafters. There are three simple cases; each is related to the third dimension but behaves principally in two dimensions. These are summarized first. Later, and against this two-dimensional introduction, the more complicated three-dimensional effects are summarized. To facilitate their comparison, each case is considered to employ the same rafter sizes and to carry the same load.

In the first case, two rafters lean against one another at the ridge line, each is supported vertically and laterally at its tail, and together they form an arch (Figure 5). In a second case, the two rafters are supported by walls that cannot resist their thrusts, and this lateral force must be sustained through a collar tie (Figure 6). Under load, the rafters bend inward, both under the load and in response to the collar tie force, and these combined effects would result in very pronounced deflections. Usually, for both of these cases, the thrusts are carried by the stiffer tie that occurs naturally if a second floor is present at or below the eave line. In a third strategy, the rafters are supported by a ridge beam (Figure 7), thrusts are avoided altogether, and the behavior of the roof is more easily understood. However, if the rafter tails are tied together, say, by the presence of a second floor, then the rafters might behave as in Figure 6, thereby eliminating the need for a ridge beam.

These two-dimensional analyses ignore the several complicated effects occurring in the third dimension—effects arising from diaphragm or plate action. Here, whole flat sections—walls, roof surfaces, and floors—are very stiff in their own plane, are joined at angles to create very stiff three-dimensional structures. The best strategy for the structural design of a single-family house is to develop the diaphragm potential of the walls, floor, and roof surfaces and to fasten them together to create a rigid "box." However, although this represents an excellent strategy for load carrying, it has profound implications for panelization. As the design requirements vary from house to house, the system design is governed by the worst-case scenario. If a standard panel is designed to some reasonable strength level, this limits the range of houses that can be built. If, instead, the panel is designed to some extreme standard, then it provides unnecessary conservatism most of the time and variable risk all of the time.

One way to imagine a panelized building system is to consider a fully constructed conventional building that is separated into manageable parts and reassembled. If the whole building employs diaphragm action, the resulting reassembly relies heavily on the panel-to-panel connections, which, in turn, emphasize the field assembly of the system. Ironically, overall system quality would rely upon quality control in the field, when, in fact, much of the point of panelization is to better exploit the quality control potential of the factory. This last point is centrally important in designing any panelized roof system, and it has special significance in understanding the strategy taken within this group.

Considering the difficulties posed by collar ties, the risk of depending upon a floor-level tie, and the above-mentioned difficulties of assembling panels into diaphragms, our system employs a substantial ridge beam and ribbed panels. The ridge beam is a composite box beam with a

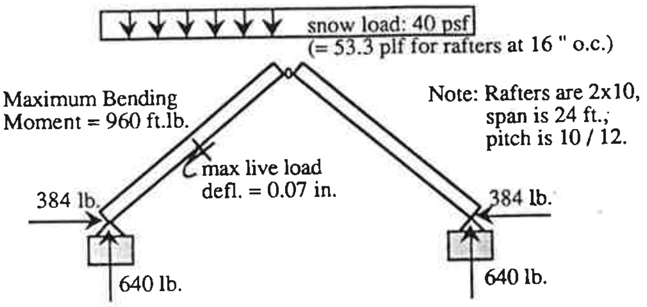


Figure 5 *Two rafters, configuration 1, supported horizontally and vertically at top of wall.*

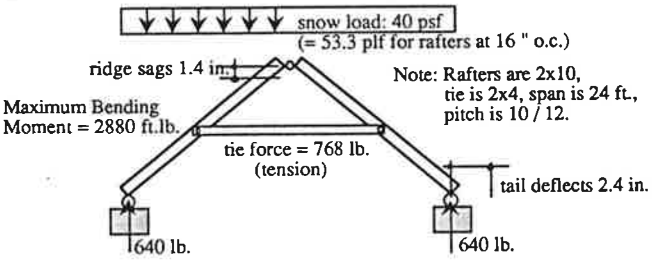


Figure 6 *Two rafters, confiugration 2, supported vertically at top of wall and tied with a collar tie.*

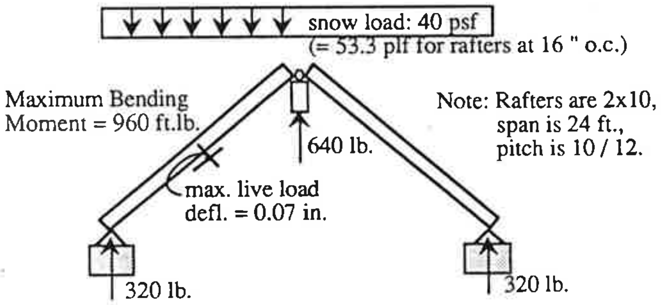


Figure 7 *Two rafters, configuration 3, supported vertically at top of wall and by a ridge beam.*

triangular cross section (Figure 2) made principally of OSB and trusses and reinforced axially with a parallel-strand lumber product. The panels are 4 feet wide, nominally 10 inches deep, and of varying lengths (Figure 1). In spanning from eave to ridge, they act as ribbed, stressed-skin, one-way composite plates. Among its many differences from conventional frame construction, the stressed-skin panel employs its faces as the primary load-carrying elements of its design. The ridge beam is important in assembling the roof, and it takes on the additional role of lateral load carrying. Finally—and taken together with the vertical supports provided for the ridge beam through endwalls, intermediate walls, or posts—the entire system meets the original goal of vertical independence.

In considering panel structural performance, deflection criteria most often limit design, and so a comparison among maximum allowable spans provides a reasonable basis for comparing panels to rafter systems. Table 1 lists the maximum allowable spans for a range of panels and rafter configurations based upon limiting the stimated long-term deflection to L/240 for live deflection (which is measurable for panels but negligible for rafters) and takes account of long-term effects. Note that in our long-term load tests (see below), both panel and rafter deflections increased over time, with a slightly greater tendency for panels than for rafters. Together with the shear deflection, this tendency combines to yield panel deflections that nearly match those of comparably sized rafter systems and, consequently, the maximum allowable spans are comparable as well.

LONG-TERM DEFLECTION STUDY

A long-term deflection study was conducted using the structural building panels. Deflections were monitored for four months while the panels were subjected to a uniform load. The load was then removed and the recovery was monitored for one and a half months.

Test Setup

The support conditions, panel size, and dial gauge locations for deflection measurements were configured according to the guidelines set forth in the ASTM E-72 panel-testing procedures for short-term load tests. There are no ASTM guidelines for long-term load tests. All panels were four feet wide, rested on rollers at both ends, and were loaded with a uniform 40-psf load. No attempt was made to control the environmental conditions (primarily humidity) during the test.

Two rib panels, one spanning 12 feet and one spanning 17 feet, were tested. In addition to the rib panels, a rafter construction spanning 12 feet was tested simultaneously. The rafter construction was made of three 2 × 10s spaced 16 inches on center and covered with 7/16-inch OSB sheathing.

TABLE 1
Panel Attributes

Panel Attributes:					
Nominal Depth	OSB Thickness	Ribs	Maximum Allowable Span	Rafter Configur-ation	Maximum Allowable Span
10"	(7/16)	(4)	16.42	2x10 @ 24" o.c.	14.30
10"	(5/8)	(3)	17.97	2x10 @ 16" o.c.	16.38
10"	(5/8)	(4)	18.25	2x10 @ 12" o.c.	17.95
12"	(7/16)	(4)	18.98	2x12 @ 24" o.c.	17.33
12"	(5/8)	(3)	20.37	2x12 @ 16" o.c.	19.82
12"	(5/8)	(4)	20.70	2x12 @ 12" o.c.	21.87

Note: Spans are computed for 4-ft-wide panel or "strip" of raftered roof, loaded perpendicularly with 40-psf uniform load, projected to long term.

Results

The specimens initially deflected and then continued to deflect more slowly for a number of days before they leveled off (see Table 2).

The specimens reacted to the amount of moisture in the air. A rough record was kept of the humidity and precipitation between each reading of the gauges. This verified a direct relationship of increased deflection with increased moisture and a slight upward recovery of the specimens with reduced moisture. The deflection fluctuations ranged from 5% to 13% of the total deflections (see Table 2).

Ideal elastic beam theory predicts that the initial recovery will equal initial deflection, after which the long-term recovery will result in the beam gradually recovering 100%. In reality, however, we expected the panels to recover less than 100%, that is, we expected that some plastic deformation would have occurred.

When unloaded after 118 days, the specimens initially (in two hours) recovered between 70% and 75% of the initial deflection. After 45 days of recovery, remaining changes in deflection were due to humidity, and elastic recovery had clearly halted (see Table 2).

There was no significant difference between the structural performance of the 12-foot rafter and the 12-foot rib panel specimens, except for the increased sensitivity to hygroscopic movement of the oriented strandboard.

Foamed Cement Cores for Sandwich Panels

Structural sandwich panels made of two stiff skins separated by a lightweight core are an attractive alternative for housing construction. The separation of the faces by the core increases the moment of inertia of the cross section with little increase in weight; as a result, sandwich panels are efficient members for resisting bending loads. Panels with foam cores can have low thermal conductivity (or high R-value), and sandwich panels are ideally suited to automated production of prefabricated components. Current sandwich panels used in housing construction have rigid polyurethane or expanded polystyrene foam cores; both have excellent thermal performance. The compliance and creep of polymer foam cores restrict their use to secondary structural elements of limited space, however. The fire resistance of polymer foam cores is poor. Polymer foams are relatively expensive as a building material (roughly $2.50/kg in 1991). For these reasons, we evaluated a wide range of possible core materials for housing construction, comparing mechanical and thermal properties, fire performance, sound absorption, moisture penetration, and constructability. The results of this comparison suggested that foamed cement is a potentially attractive material: it has a high stiffness, low creep, excellent fire resistance, and low cost. The thermal resistance is lower than polymer foams; the low cost of cement foams allows compensation for this

TABLE 2
Results of Long-Term Deflection Study

	Rafter, 12-ft span	Rib panel, 12-ft span	Rib panel, 17-ft span
Initial deflections (after one hour).	.210" L/686	.198" L/727	.585" L/349
Long-term deflections (after indicated time period).	.291" L/495 8 days	.313" L/460 8 days	.963" L/212 14 days
Fluctuations in deflection, in inches. As a percent of total deflection.	.015" 5% 110 days	.041" 13% 110 days	069" 7% 104 days
Initial recovery, in inches recovered. Percent of initial deflection recovered during initial recovery (two hours).	.154" 73%	.139" 70%	.436" 75%
Deflection remaining after recovery. Percent of total deflection recovered.	.116" 61% 45 days	.110" 63% 45 days	.440" 55% 45 days

L = span length in inches.

through the use of thicker sections. The main limitation of cement foams is their low tensile strength and ductility. In this part of the project, our goal was to characterize the mechanical properties of cement foams and, if necessary, improve them.

Cement foams ranging in density from 160 to 1,600 kg/m^3 were made by mixing a preformed foam with a cement slurry. The mix design for a 320 kg/m^3 cement foam is described in Table 3. The slurry coats the cell surfaces of the preformed foam, which remains stable until the cement hardens. Three-inch diameter, six-inch-high cylinders and 2-inch × 2-inch × 8-inch beams were made. Load-deflection plots from compressive tests on the cylinders were used to obtain values for Young's modulus and the compressive strength. The ultimate load from bending tests on the beams was used to obtain values for the modulus of rupture. The results of the tests for a 240-kg/m^3 cement foam are summarized in Table 3; additional results for other densities of cement foam are reported by Tonyan and Gibson. As the density of the cement foam is reduced, the thermal resistance (R-value) increases. At 240 kg/m^3, the thermal conductivity value is estimated to be .041 W/m·C using the model of Glicksman and Torpey (1987). At this density, the modulus of rupture is 0.07 MPa, lower than that required for housing panels. We next considered means of improving the mechanical properties of cement foams.

The cell walls of foams deform primarily by bending. By making the cell walls into sandwich members, the mechanical properties of a foam can be improved (Tonyan and Gibson); we call such foams "microsandwich foams." Microsandwich cement foams were made by introducing a high volume fraction (50%) of low-density (48 kg/m^3), 5-mm-diameter expanded polystyrene foam spheres while cement foam forms between the spheres. The resulting microstructure is a microsandwich cement foam (Figure 8). The mechanical properties of the microsandwich cement foam were measured using the same techniques as those used for the plain cement foams. Their properties are listed in Table 4.

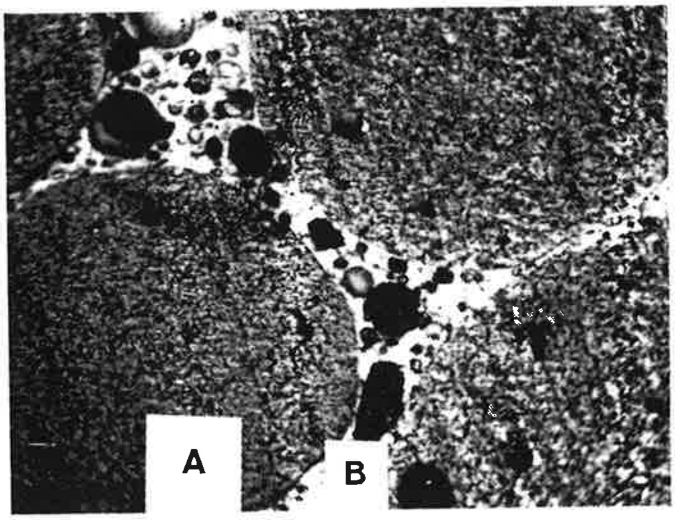


Figure 8 *Fifty percent by volume of expanded polystyrene spheres (A) in cement, (B) giving "microsandwich" cell wall structure.*

For comparison, Table 4 also lists properties of 32-kg/m^3 rigid polyurethane foam and 16 to 32 kg/m^3 expanded polystyrene foam. The density of a composite cement foam is still higher than comparable polymer foams, but this is compensated for by its much lower cost. The Young's modulus of the cement composite foams is about 140 MPa, 10 times that of polymer foam cores, reducing the contribution of shear deflections in the core to the total deflection of a panel. As a result, creep is not expected to be a problem with cement/EPS composite foam core panels. The compressive and tensile strengths are roughly equal, suggesting that the largest crack within the composite cement foam is on the order of the cell size. The thermal resistance of the composite cement foam is lower than the polymers, but, again, if a thicker panel is used, comparable overall R-values can be achieved. Cement composite foams are more fire resistant than polymer foams. Specimens with a surface skin of cement do not burn under a propane torch. Specimens with a cut surface, exposing the polystyrene

TABLE 3
Cement Foam Core

Component	Weight (N)
Water (49°C)	23.4
Cement	44.5
Microsilica	6.50
Polyester fibre (38 mm)	0.15
Superplasticizer	0.22
Preformed foam	8.86 (0.02m^3

TABLE 4
Comparison of Core Materials for Building Panels

Property	Cement Foam	Microsandwich Cement Foam	Poly-urethane Foam	Poly-styrene Foam
ρ (kg/m^3)	240	192	32	16.32
E (MPa)	70	140	10-14	5.4-11
σ_c (MPa)	0.14	0.38	0.14-0.17	0.10-0.14
σ_t (MPa)	0.07	0.38	0.17-0.28	0.10-0.14
Thermal Conductivity W/m°	0.073	0.048	0.018 - 0.024	0.036
Cost ($/kg)	0.22	1.34	3.36	2.24

spheres, self-extinguished after the exposed polystyrene beads melted under the propane torch, since beads are surrounded by the cement foam.

Additional research and development is needed to make a practical cement foam core building panel. The densities and mechanical properties achieved using the cement/polystyrene composite foam demonstrate that cement composite foams possess considerable potential for use in building panel cores.

CONCLUSIONS

Rib panels using oriented strandboard for the rib and faces form the basis for a new net-shaped roof system. The panels have better thermal performance than rafter construction, and they lend themselves to a system that can be fabricated off site. A proof-of-concept structure has demonstrated the advantages of such a rapidly erectable system.

Low-density foamed cement can be used as the core of a sandwich panel that has good structural and thermal properties. The mechanical properties of the foam are increased by the introduction of low-density spheres into the foamed cement.

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