THE DESIGN OF A PANELIZED ROOF SYSTEM FOR RESIDENTIAL CONSTRUCTION

by

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Submitted to the Department of Architecture on May 10, 1991 in partial fulfillment of the requirements for the degree of Master of Science in Building Technology

Abstract

The cost of housing in the U.S. continues to rise faster than household income. Innovative building materials and construction technologies have the potential to reduce housing construction costs. One strategy to do this is componentization. There is a longstanding trend towards the increased use of components in U.S. residential construction. One such type of component is the composite building panel, used for walls, roofs and floors. Presently the types of composite panels used in residential construction include pre-framed walls of standard construction and, more innovatively, structural foam-core panels with wood or wood composite faces.

This thesis focuses on the design of a panelized roofing system for residential construction. The roof was chosen for various reasons. It includes some of the most complicated geometrical and structural challenges. It is often the most difficult area of the house to frame conventionally. Its construction is a crucial step in getting the house weathertight. For these reasons and others builders have identified it as a prime target for innovation.

The design of the panelized roof system is illustrated as a tree of decisions. The path traveled down this tree led to a ribbed panel spanning from eave to ridge. A design selection method developed by Stuart Pugh was used to design the connection details of the system. The interdisciplinary design process used to design the roof system is examined and evaluated in light of the results it yielded.

Mock-ups, models and a full scale proof-of-concept structure were built. These constructions were used as learning tools during design and to demonstrate and evaluate the performance of the roof system design.

Thesis Supervisor: Dr. Leonard Morse-Fortier
Title: Assistant Professor of Building Technology

Acknowledgements

First, I would like to thank the people involved in the Innovative Housing Construction Technologies Program at MIT (IHCTP). This work would not have been possible without the cooperation of these faculty, researchers and students. I would especially like to express my gratitude to the people who participated in the, sometimes tedious, joint design process: Prof. Leonard Morse-Fortier, Prof. Carl Peterson, John Crowley, Michel Parent and Mohammed Maleej. Also, thanks are due John Pflueger for introducing me to the Pugh process, and Mark Kucirka and Mike Toole for helping me understand the project's background.

I was fortunate to have three advisors, all of whom took a sincere interest and active role in my work. I would like to thank each of them: Prof. Leonard Morse-Fortier of the building technology program, for the great amount of time and effort he spent with me on the project, for his contageous enthusiasm and for his friendship; John Crowley, a Research Associate in Architecture for his knowledge and advice; Prof. Leon Glicksman, head of the building technology program, for his academic guidance and 'big picture' view of the project.

The very nature of this thesis being an integration of many specialties into the design of a complex system, means that many of the ideas and research contained herein originated with people other than the author. Where possible, credit has been given to those responsible, however, many of the concepts were collaberative efforts where no one person alone owns the idea. I would like to thank all those who shared their ideas, for they will recognize some form of them in here.

I appreciate the funds provided by the Innovative Housing Construction Technologies Consortium that made this work possible.

Finally, I want to thank the guys who helped me carry the 16', 250 lb panels up to the fourth floor: Ruel, Kris, Ben, Paul, Dave, Kevy, and Mohammed. I still owe some of you ice cream.

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CHAPTER 1 Introduction

1.1 The rationale for technological innovation in housing

Housing costs have increased relative to household income over the past few decades. Homeownership rates are declining, especially among younger households. The high cost of buying a first house has forced many people to delay or give up the effort to become a homeowner [Harvard U., 89]. Part of this rise in housing costs is attributable to higher construction costs, and other costs influenced by construction factors; such as construction time. In 1982, the U.S. General Accounting Office reported that greater use of innovative building materials and construction techniques could reduce housing costs.

The technology of materials and manufacturing has advanced considerably in the past 20 years, but application of these advances to whole building systems for housing has lagged. The emergence of large, national builders enables larger investment to take place in the form of research, development and facilities. Also, there is an opportunity for use in the U.S. of technologies from Europe and Japan to apply to housing (similar to the way Japan borrowed the 2 x 4 building system from the U.S.). If this opportunity is ignored, it may become a threat of competition from large overseas builders who may work in partnership with U.S. firms. This demands a greater commitment to applied building research in the U.S.

A number of demographic factors also influence the need for innovation in housing construction. It is predicted that the U.S. workforce will increase at the slowest rate since the 1930's. The construction industry traditionally depends on male workers, under 35 years of age, to replace retiring workers. This group is expected to decline by 3.5 million over the next ten years. These factors mean that homebuilders will face unprecedented problems finding workers with construction trade skills in the future [NAHB, 91], [US DOL, 88].

Current house construction practice is problematic and becoming more so. Quality control of stick-frame houses is difficult, particularly with a decline in the availability of skilled workers. Stick-frame construction is inefficient in that it does not lend itself to economies of scale except on large tracts (California builders put the limit at 30 houses). As these large development tracts become fewer, smaller scattered site, or infill, developments become the norm and the problem of inefficiencies becomes more important. Finally, rising costs of traditional materials for stick-frame construction will continue to drive up the cost of housing.

Many attempts have been made at lowering the cost of housing construction in the U.S. through technological innovation. The largest being the Department of Housing and Urban Development's Operation Breakthrough in the early 1970's. Unlike many of these technical efforts, the Innovative Housing Construction Technologies Program (IHCTP) at MIT is approaching the problem with a broader approach. Not only is the physical building system being looked at, but also, the system in the context of the U.S. homebuilding industry's conservative, evolutionary nature. This approach examines industry structure, distribution channels, the service part of the homebuilding industry, the investment potential the industry posses, and most importantly, the market demands. Another important distinction, as discussed in section 3.4, is that the IHCTP is not focussing exclusively on low cost housing, but rather on solutions that apply to all housing market segments based on their viability in the marketplace. As further explained below, the goal of the IHCTP is to identify and develop products to satisfy the next logical step in the continuing evolution of residential construction.

1.2 The Innovative Housing Construction Technologies Program

This thesis is based upon research completed with the Innovative Housing Construction Technologies Program (IHCTP). The main goal of the IHCTP is to identify and propose innovative techniques to significantly improve both the quality and affordability of newly constructed housing in the U.S. The objective is not to revolutionize the design of houses but to see where new materials and manufacturing methods can bring to market products which would fit easily into the existing homebuilding industry. It is important to note that the IHCTP is not an attempt to come up with the definitive "MIT" building system. Rather, it is to establish strategies, investigate options, determine viability of concepts to the point where industry may decide to invest to further develop and commercialize some of these concepts. Within the program, research is ongoing in the areas of materials, manufacturing, building systems design, and the home building industry. The IHCTP has divided its research efforts into three development time horizons at the end of which a concept may reach the market. These are the short (2-3 years), medium (3-5 years) and long term (5-10 years) time horizons. The work in this thesis is directed toward the short time horizon.

An important feature of the IHCTP is its interdisciplinary composition. Participants are drawn from many departments and labs at MIT, including the departments of architecture, mechanical engineering, civil engineering, management, and the Laboratory for Manufacturing and Productivity. The program is divided into smaller projects in the four areas of research mentioned above and within these various departments. The projects frequently interact through the project group leaders and in regular meetings. This multidisciplinary approach ensures that the projects do not sidetrack onto directions either non-economical or unrealistic with respect to the constraints of the other disciplines.

The IHCTP at MIT is sponsored by manufacturers of basic building materials and products for residential and light commercial construction. In addition to the sponsors, the

IHCTP has assembled an advisory board. This board consists mainly of companies using these basic materials to build houses or components for houses, including roof and floor trusses, foam core building panels, panelized home packages and modular homes. The National Association of Home Builders and the model code agencies are also members of the advisory board. The expertise and resources of the sponsors and the advisory board are important to furthering the IHCTP's goals of finding innovative home construction techniques. Where their input has been particularly important to the design work in this thesis, it is noted as such.

IHCTP sponsorship during this thesis work:

Alcan International Ltd.
Certainteed Corp.
DOW Chemical
GAF Corporation
General Electric Plastics
Hoechst-Celanese
Illinois Tool Works
MacMillan Bloedel Ltd.
Mobay Chemical Corp.
USG Corporation
Weyerhauser Company

Advisory board:

Acorn Structures
Atlas Industries
Gebhardt Associates
Maison Bouygues
MiTek Industries, Inc.
Mykonos Corporation
National Assoc. of Homebuilders
NVR Building Products Co.
The Ryland Group, Inc.
Southern. Bldg. Code Cong. Internat., Inc.
Today's Building Systems, Inc.
Winchester Homes, Inc.
Winter Panel Corporation
Wood Structures, Inc.

To pursue its goal, the IHCTP has chosen to follow the trend in U.S. residential construction toward the use of building components fabricated off site, known as componentization. Successful components include windows, pre-hung doors, staircases and roof and floor trusses. These components are accepted either because they add value to a house more efficiently than the builder can do it on site, or in a way that the builder is incapable of doing. Although generally conservative, builders eventually accept new components because they bring them better quality, lower costs, fewer delays and less variation in these items, resulting in reduced risk. The project objective is to design and test new house components using new materials and new manufacturing techniques.

Initial study led the IHCTP to further narrow its focus to a component system for the roof of single-family detached (SFD) houses. The components took the form of panels which, aggregated into a complete building system, form the subject of this thesis. The decisions to focus on a roof panel system for SFDs are explored in detail in following chapters.

1.3 The role of this thesis

As mentioned in section 1.1, the development of a building system requires the participation of many disciplines, which is reflected in the make-up of the sponsors, advisors and researchers involved in the IHCTP. During the course of research, graduate students focused on specific areas of work. These students, under their advisors, worked on more narrowly focused projects whose value to the IHCTP project depended on their being integrated into the overall building system. In the building system design work of this thesis, the work of these various students has been incorporated as it feeds back into the knowledge base of the project. An analogy can be drawn between this process and the case in industry where the architect brings together the work of the engineers and other specialists into the design of a building. In this case the design is not a building, but a building system for roofs. Because of this arrangement, much of the background work that the panel system design is based upon was done by others and is not repeated here.

As explained later, the process of designing the roof panel system can be illustrated as a tree of decisions. Chapter 4 presents the decision tree in detail, starting with the basic goals of the IHCTP. It should be noted that work on this thesis did not begin until several levels below this starting point. Key decisions had already been made about the focus of the research efforts. These decisions are explained in a manner consistent with the remainder of the decision tree. Prior decisions at levels two, three and four had already narrowed the project to focus on stressed skin panels for the roofs of residential dwellings. The roof was chosen because it is a clearly defined subsystem with strict performance requirements, for which a need for improvement has been identified in the marketplace (section 4.1.3). The decision at level one, the type of housing, was not yet finalized, but a strong leaning toward SFDs was already evident for purposes of focusing the design efforts. The intent, however, always was to have the system apply to single family attached and light commercial construction as well.

The thesis begins with an introduction to the IHCTP and an explanation of how this thesis fits into it. Following that is a review of the conventional stick-frame method of residential construction in the U.S., along with a construction cost breakdown of a typical home. Four common prefabrication techniques are described along with the trend toward the componentization of U.S. residential construction. Chapter three describes the design goals for the building system. Chapter four presents the tree of decisions the design process followed and explains the decisions made at each level of the tree. The fifth chapter goes over the structured design-selection method used to design the system joints and presents an example of a design session for a specific joint. Next is a description of a proof-of-concept (POC) structure built by the IHCTP in the spring of 1991. Much of the work in this thesis was directed towards the design of the POC, which utilizes the roof panel system. Chapter six also includes the details of the panelized roof system panel and joints. Chapter seven briefly presents some of the implications the system may have on architectural design and the construction industry. Finally, there is a critique of the design process and some concluding thoughts on componentization and the role of panels. The appendices includes a compilation of additional design ideas and a record of some of the pros and cons of the many joint concepts considered.

While this thesis focuses on the design of a panelized roof system, other theses written in conjunction with the IHCTP address related issues in more detail. The other issues examined include a detailed structural analysis of different types of panelized roofs and their joints [Kucirka, 89], the past and present of prefabrication and the foam panel building industry [Toole, 90] and materials for roof panels, specifically lightweight cement foam as the core material in a sandwich panel [Tonyan, 91]. These works serve as background for this thesis and information from them has been incorporated into the roof system design. For a more detailed discussion of these topics, the reader is directed to these sources.

CHAPTER 2 Background

2.1 Review of conventional stick frame construction

The stick frame, or 2 x 4, western platform building system dominates U.S. homebuilding. Most single family homes consist of a masonry or concrete foundation, constructed at the job site, and supporting a wood skeleton (figure 2.1). The wood skeleton is an assembly of parts - studs, headers, joists, rafters, plates, etc. - fabricated on the site from dimension lumber to create the wall, floor and roof frame. The exterior walls are usually wrapped with structural sheathing (traditionally plywood; now commonly OSB or waferboard), then window and door components are installed, followed by cladding and trim. The cladding ranges from cedar shingles to stucco to vinyl siding. The floor joists are covered with subfloor sheathing. The roof structure is built of trusses or rafters, covered with structural sheathing, a layer of felt paper, and finish cladding (most commonly asphalt shingles) and trim.

Roof trusses (figure 2.2) have had a great impact on housing construction. They are an example of a successful component, rising to capture a huge share of the market in the 20 years since being introduced. They are made of 2 x 4 or 2 x 6 dimensional lumber held together with steel truss plates. The drawback of trusses is their lack of design flexibility if one tries to inhabit the roof cavity space (section 3.5). Rafter roofs are framed with 2 x 8 to 2 x 12 lumber similarly to floors. They are very flexible but time consuming to build and require highly skilled workers.

Within the walls of the house, cavities are fitted with electrical wiring, plumbing and mechanical systems followed by insulation in the exterior walls (usually fiberglass batts). Insulation may also be added in the form of foil-faced rigid foam insulation

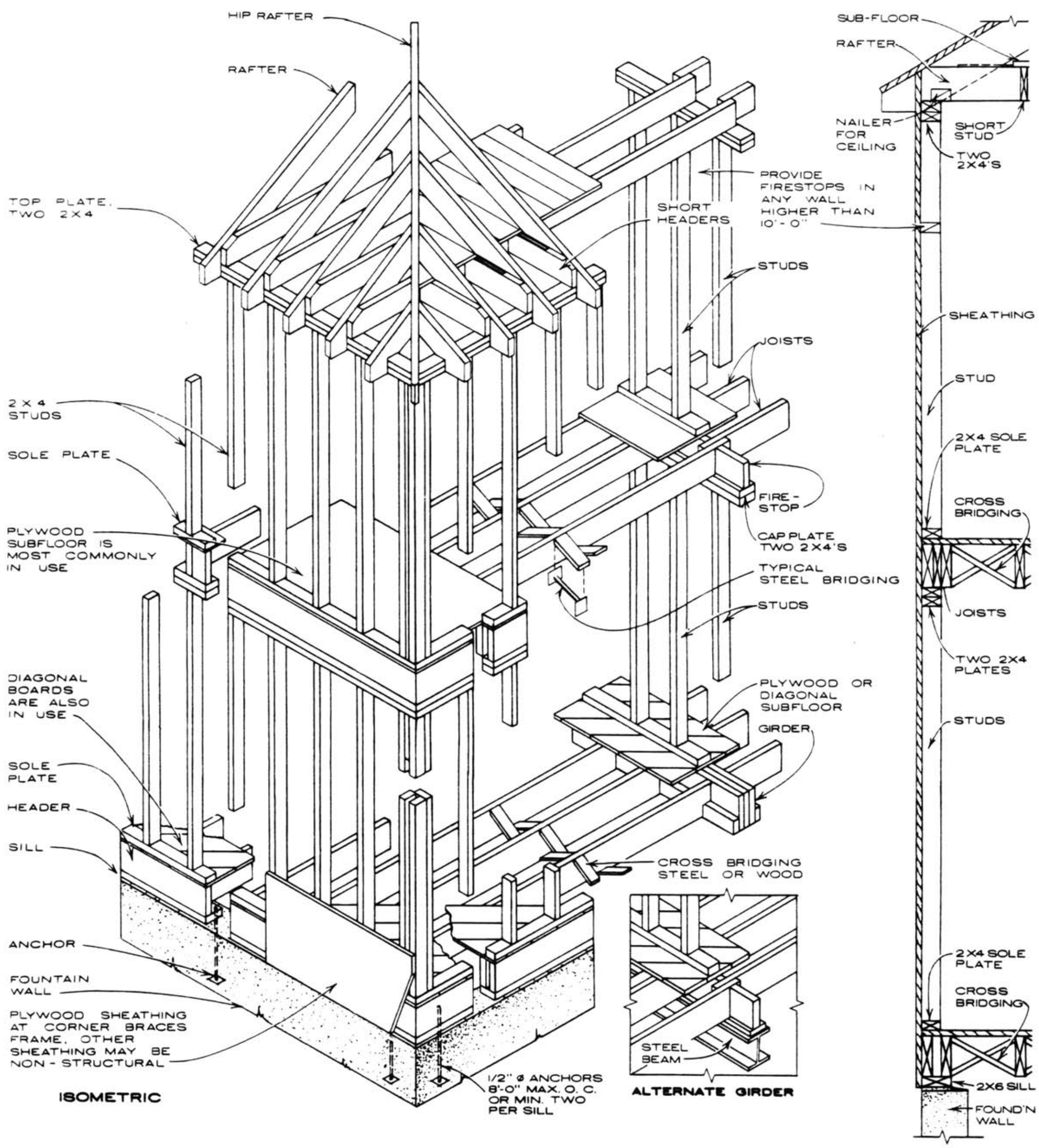

Figure 2.1 : Conventional platform framing
Source: [Ramsey/Sleeper, 81]

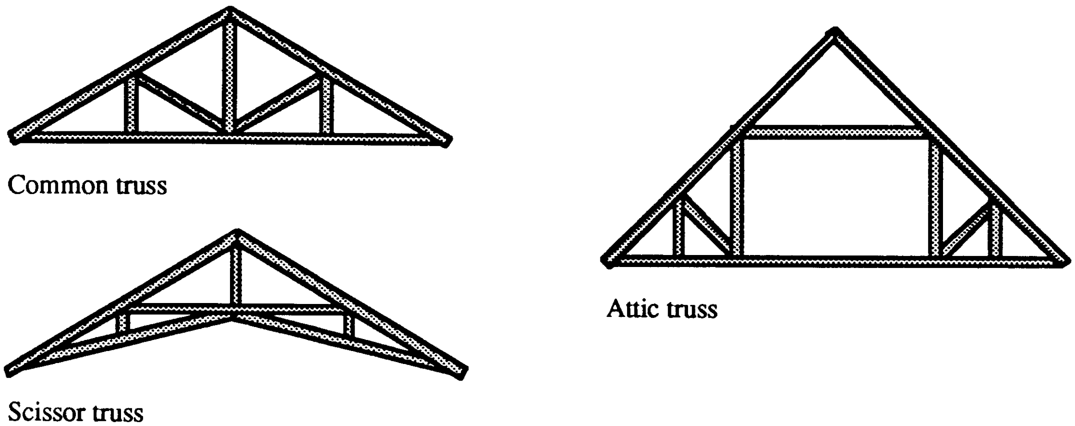

Figure 2.2 : Common roof trusses

sheathing on the outside of the studs. The interiors of the walls are commonly covered with gypsum board and finished with jointing compound, paint and trim.

This system of wood frame and cladding has proven highly versatile. It has demonstrated an ability to accommodate almost an infinite design variety - from simple economical homes to the most luxurious and complex. Table 2.1 presents a construction cost breakdown for wood frame houses.

Table 2.1 : Percent of total construction cost for conventional stick-frame construction and open panel construction of single family homes

	Chicago suburb*	**Mid-atlantic Stick-built****	**Mid-atlantic Open-panel****	**National NAHB*****
Foundation	12.5	7.2	14.7	11.6
Site	3.8	8.6	5.1	3.5
Framing	27.1	19.8	27.0	21.9
Exterior Walls	10.7	17.1	11.4	8.0
Roofing	3.0	1.4	0.5	3.4
Interior	18.5	18.3	17.7	20.1
Mechanical	10.1	15.3	11.9	10.5
Electrical	5.0	5.3	3.7	4.8
Specialties	3.5	5.1	4.8	11.3
Other	5.8	1.3	2.9	4.9

(Percentages may not total 100% due to rounding)
*Sources: * Cambridge Homes, Libertyville, IL*
*** [Crowley, 89]*
**** [NAHB, 90]*

Presently, a conventional house frame is customized to receive standard, pre-manufactured building components. The trend toward componentization (section 2.4) means that the frame is increasingly becoming a receptacle for value-added building components. The wood frame provides project-specific design flexibility, while simultaneously accepting standardized building components.

2.2 Current technology in prefabricated residential construction in the U.S.

Manufactured housing is typically divided into four groups: HUD-code (mobile homes), modular (also called sectional), panelized and pre-cut. Table 2.2 shows the construction time, close-in time and crew size for these systems. Figure 2.2 shows the total market share of single family detached houses for each building system. The market share of these prefabrication systems is far from uniform across the U.S. [Hallahan, 89]. Modular market share ranges from less than 1% in the West to 7% in the Northeast. Panelized construction ranges from 4-7% in the West to 25 - 29% in the Midwest and Southeast. These numbers reflect the increased applicability of these systems under market conditions more suitable to their use. The higher local numbers suggest that overall increased market share is possible as conditions across the U.S. change.

2.2.1 HUD code mobile homes

HUD-code houses are homes built according to a code implemented by the Department of Housing and Urban Development, Manufactured Homes Construction and

Table 2.2 : Approximate construction time and crew size for five methods of construction. A building is considered weathertight, or tight, when all exterior sheathing, windows and doors have been installed.

	Days under construction (site work only)	**Days to weathertight**	**Crew size**
Conventional	80-120	15-50	5
HUD-code	10-20	1-2	5
Modular	20-60	1-2	5
Panelized	40-90	1-10	5
Pre-cut	80-120	15-50	5

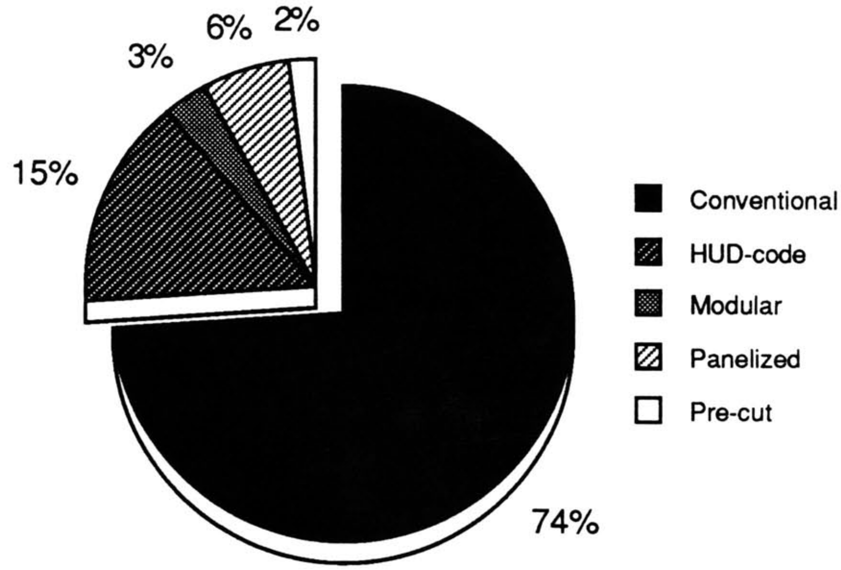

Figure 2.3 : U.S. market share of homebuilding systems 1987
Source: [LSI/F.W. Dodge, 88]

Safety Standards in 1976 for mobile-type homes. This code supersedes state and local codes for this type of housing. Most HUD-code houses include a metal chasis in the floor and either light gauge metal or wood framing. They can be single wide, leaving the factory 100% complete, requiring only utility hook-ups, or double wide, requiring one to three weeks site finish work. They are sold through local dealers and usually resemble plain one story stick built houses.

2.2.2 Modular

Modular (or sectional) single family houses are commonly built up of two to six large three dimensional boxes. These sections, or modules, are usually stick framed in a factory, complete with fixtures and finishes. They are then stacked vertically or joined side by side in a variety of configurations at the site. Three to eight weeks of finish (or button-up) work is then required. Modular homes are usually assembled into single family detached houses but can also be assembled into multi-family housing up to three stories high.

2.2.3 Panelized

Panelized home packages are pre-designed home packages that come to the site in the form of wall and floor panels and either roof trusses or panels. They may also include modular utility cores. The wall panels are often large and may comprise the whole side of a one story house. Section 2.3 provides a more detailed discussion about the types of panels available.

2.2.4 Pre-cut

Pre-cut house construction is relatively uncommon. A pre-cut home consists of conventional construction materials that are cut and labeled in the factory, shipped to the site, and installed using mainly standard practices. There is a very low degree of prefabrication and therefore the site work duration does not differ dramatically from conventional construction. Log Homes, once a very popular house kit, would fall into this category.

2.3 Current residential panel technology

The following is a brief summary of current technology in panelized residential construction in the U.S. Residential building panels can be divided into two broad categories - stick-framed panels and foam-core panels.

Stick-framed panels are similar to conventional construction in that the materials and assembly details are nearly identical. The difference is in where the labor is performed. In this type of construction, the wall, and occasionally floor and roof sections are prefabricated in a factory and brought to the site whole. These wall panels are often very large and may comprise the entire length of a one storey house. The floors are often pre-framed into panels as well in stick framed panelized construction. The roofs, however, are usually not pre-framed. They are either conventionally framed with rafters or, more likely, built with trusses.

Within this type of panel are two classes - open-wall panels and closed-wall panels. These terms refer to the degree of value added to the prefabricated product. Open wall panels contain the framing, exterior sheathing and windows. Closed wall panels also include electrical work, plumbing work, insulation, exterior siding and the interior sheathing (usually gypsum wall board).

Two major problems, one political and one technical, have plagued attempts at closed wall panel construction. Since site inspection by the local building official is impossible when the walls arrive closed-in, arrangements must be made for a third party inspector to inspect the walls in the factory. Most states have legal provisions for this, however initial approval of a manufacturer's system can take 6 months and approving a change in the system takes 1 to 2 months. This causes a manufacturer to be slow to respond to the market. The technical problem is that there is a greater potential for shipping and erection induced damage to the more delicate interior finish materials of a closed wall panel. Of the approximately 130,000 stud-framed panel homes built in the U.S. each year from 1984 to 1988, only 2% were closed wall.

Stressed-skin panels are a version of the stud-framed panel. They are a type of panel in which plywood (or other sheathing material) faces are glued firmly to both sides of a frame (usually 2x dimensional lumber). The skins and frame work together resulting in a panel stiffness much greater than that implied by its parts. Structural foam core sandwich panels (see below) are also sometimes referred to as stressed-skin panels.

The second category of panels is foam-core panels. For a more in depth discussion of foam core panels an excellent source is Foam-Core Panels & Building Systems: Principles and Practice Plus Product Directory by Stephen Andrews [Andrews, 88]. This category can be further divided into structural sandwich panels with faces and foam panels incorporating framing members with no faces. Here, the discussion will focus on the more common structural sandwich panels with faces.

Structural sandwich panels consist of a foam core sandwiched between two faces (figure 2.4). The foam core can be either polystyrene (EPS - expanded or extruded) or urethane (polyurethane or polyisocyanurate). Polyurethane and polyisocyanurate are two very similar chemicals, here both referred to as urethane. They are closed cell plastic foams that contain low conductivity freon gas in the cells. Core densities for both urethane and EPS are commonly one to two pounds per cubic foot. The panel faces are often plywood, waferboard or oriented strand board. In the case of non-load bearing curtain wall panels used to clad timberframe (post and beam) homes, drywall is often used on the interior face. In bending, a foam core sandwich panel is structurally analogous to an I-beam. The low density core functions as the web and the high density faces as the flanges (see figure 2.5)

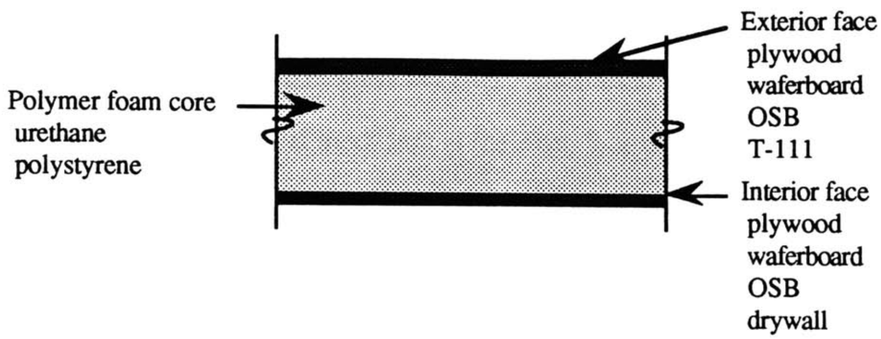

Figure 2.4 : Cross-section of a sandwich panel

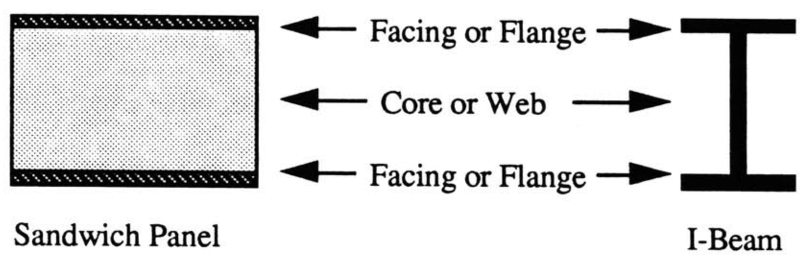

Figure 2.5 : Analogy of structural foam-core panel with a steel I-beam

[Andrews, 88]. In plane, the panels are very stiff in shear and provide considerable resistance to lateral forces.

Foam core panels allow great design flexibility, in that the four by eight foot building units can be site cut with conventional tools and the connection system is very flexible. The most common method of fastening panels together is with a spline. There are many versions of the spline as illustrated in figure 2.6.

The stud-framed panels described above are most often used in pre-designed home packages. Foam core sandwich panels are most often used as components in custom designed homes, thereby exploiting their high degree of design flexibility. Overall, panel systems are incomplete, in that they do not usually include the floor or roof.

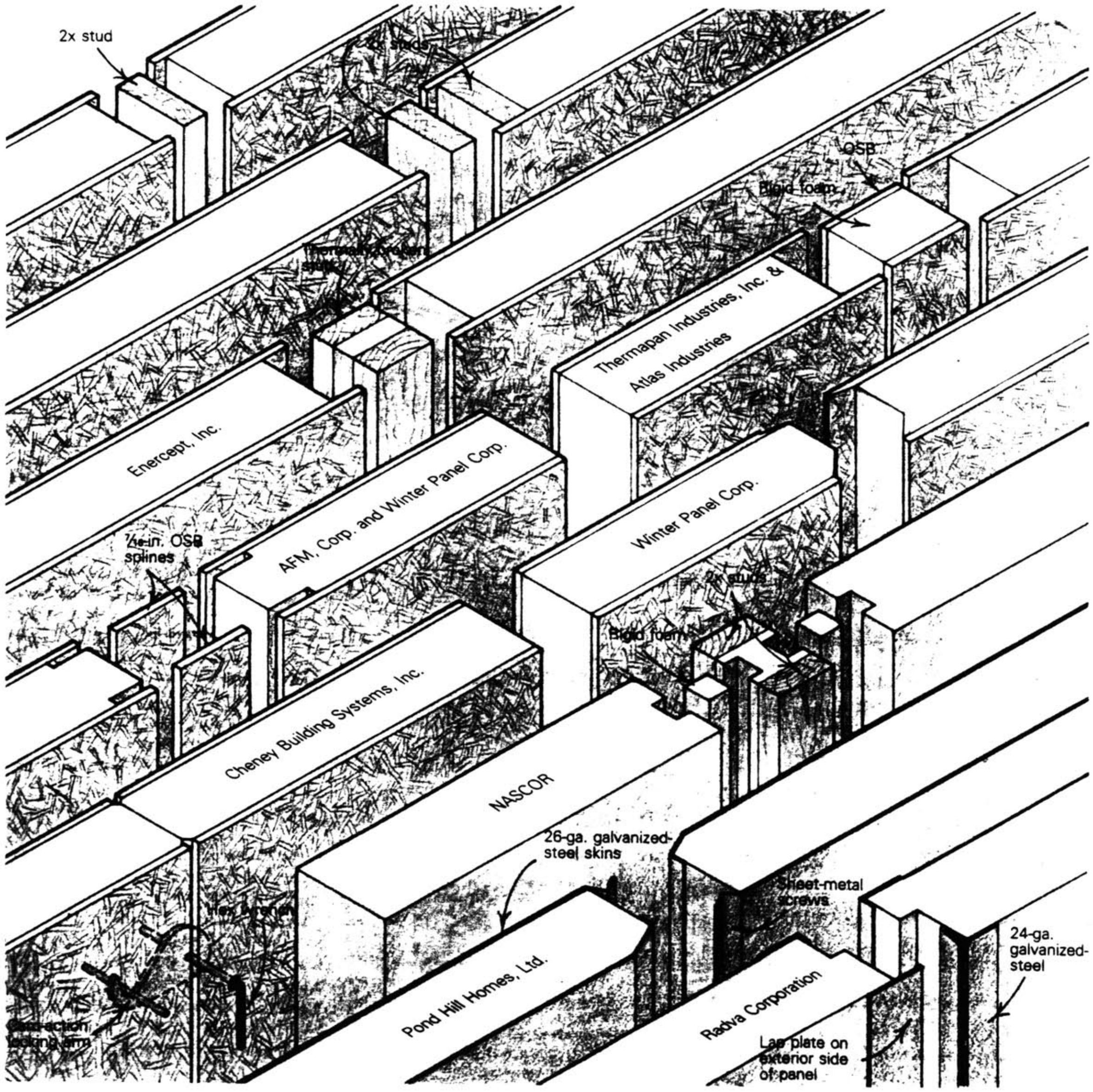

Figure 2.6 : Foam-core panel joints currently in use
Source: [Andrews, 90]

2.4 Components in residential construction, or The value-added approach to homebuilding

Throughout the Twentieth Century, housing construction has undergone large changes. Individually, these changes have not been sudden or revolutionary, but rather have been continuous and evolutionary. The change in the U.S. residential construction industry can be described as a trend toward the use of building components fabricated off site. Homebuilding has moved from a custom, labor intensive industry to a largely industrialized factory driven process. Housing construction, as perceived on the building site, is today merely the last step of a manufacturing process which involves the manufacturing and assembly of a large number of parts of varying complexity. Most of these parts come from industrial manufacturing facilities and are referred to here as building components.

In the Nineteenth century, except for a small number of prefabricated home kits sold from catalogues, most residential construction was custom built on the job site by skilled craftsmen or the homeowners themselves. These workers constructed a dwelling from the most basic of raw materials - raw lumber, glass, stones, etc. Windows were glazed, doors were fabricated and hung, fireplaces were built brick by brick, all on a one by one basis.

As industrialization entered the housing industry this way of building changed. Standard size lumber, plywood and sheetrock were some of the earliest products to appear. One of the first high value-added components to be built off site was the window. The Andersen Corporation introduced into North America the first pre-assembled window in 1932. It could be made cheaper and with higher quality in a factory. Buying the windows pre-made was much easier and quicker for a builder to do, and it eliminated a jobsite skill that the builder previously needed. Kitchen cabinets is another good example of componentization. Until the early 1960's, they were almost always built by craftsmen on the site. Now they are usually mass produced in factories and shipped through distributors to the site, where they are installed. Componentization progressed to eventually include many parts of the house (table 2.2). Now, it is possible to build nearly an entire house by assembling pre-fabricated components, both off the shelf items and custom factory-made parts. Many people in the residential construction industry believe that components are the most promising concept for decreasing the cost and increasing the performance of housing.

Table 2.2 : Components in use today and the site method or trade they replaced.

Component	**Replaced trade or method**
windows and skylights	glazier
pre-hung doors	hanging doors
staircases	highly skilled carpentry
roof trusses	rafter framing
floor trusses	joist framing
Engineered wood structural members such as LVL, Glue-Lam, Para-Lam, wood I-beams	built-up dimensional lumber
pre-fabricated fireplaces and chimneys	bricklayer
plumbing trees	plumbing site work
electrical octopuses	electrical site work
envelope parts, wall & roof panels	framing, sheathing, drywall and insulation
pre-fab trim and moulding pieces	custom mill work
kitchen and bathroom cabinets	cabinet craftsmen
moulded bath tubs & shower stalls	plumbing, tile setting
countertops and other built-in furniture pieces	custom mill work
prefabricated gutters	

These components are sub-assemblies that come to the construction site ready to be installed into the building shell. Components are usually parts of the building that have a concentration of value in them; in either materials or labor. Since they are fabricated off-site in a factory with a controlled environment, they can use manufacturing methods and equipment not available on a construction site. Some of the products built in this way, such as windows and plumbing fixtures, are standardized in dimension and in their interface with the building frame. Others, such as roof trusses and stairs, are customized according to the plans of the house. This method of construction can be termed construction-by-installation. Components reduce the skill requirements required at the job site. The numerous trades once required to serve the builder, have moved to the factory and builders have became installers of factory-fabricated components and pre-finished assemblies. The overall strategy of componentization is to reduce the fabrication and assembly requirements at the job site (figure 2.7).

Fabrication → Assembly → Installation

Component Value $$ ⟶

Figure 2.7 : Componentization

One reason for the acceptance of pre-fabricated components was that builders could take an "a la carte" approach to using them. Componentization does not try to impose a rigid, or closed, building system on the builder. Rather, the components are all designed to be compatible with the standard residential construction method of the past fifty years - the 2x stick frame. A builder can use or not use components for any part of the house depending on his or her skills, the customer's desires or the current market situation.

Component use fluctuates with general market conditions. In a slow period builders will often choose to not use certain components because cheap labor is available and they may want to retain their regular crew by keeping them working on a job for a longer time. In a busier period, a builder may use components that they would normally not use, due to a shortage of skilled labor or a need to hasten the construction process.

Another argument supporting the increased use of components in residential construction stems from the growing congestion of America's urban and suburban areas. Large tracts of land for housing are becoming increasingly rare. They are only to be found in some areas of the West. Subdivisions of hundreds of lots have historically enabled builders to set up very efficient construction operations in an "inverse assembly line" method. Specialized crews move from house to house repeating the same task of framing, siding, roofing, drywall, etc. Some builders even set up prefabrication plants on site for a specific project. As large developable tracts have become less common and consumer preference has leaned toward more individualized houses, builders have been forced to abandon this efficient way of site building and high density, scattered-lot development (lots suitable for one to a dozen homes) is becoming the predominant way of homebuilding.

Factory produced components are better suited to scattered-lot development. The increased efficiencies once enjoyed by the large-tract builder are being transferred into local or regional factories. Standardized components can be shipped to scattered sites as easily as they can be sent to large developments. These factories require greater capital investment in the short term but will be able to provide components for more homes in the long run.

In short, there are three fundamental differences between components and the other four building systems (HUD-code, modular, panelized and pre-cut) that are responsible for the greater growth of components [Toole, 90]:

• The nature of the other systems being complete house packages limits their architectural design flexibility beyond acceptable bounds in many markets. Contrarily, the "a la carte" selectability of components provides great design flexibility.

• Components have the optimal amount of work done in the factory given the manufacturing technology and site labor situation today. Modular and mobile homes have too much, resulting in a lack of design flexibility and high shipping costs, and pre-cut have too little, its assembly being little different from stick framing (section 4.1.4).

• Components benefit from *systems* improvement while the others still rely largely on conventional construction materials and assemblies.

CHAPTER 3 Design goals of roof system

This section describes the characteristics that a panelized roof system should have to be successful in the marketplace. As explained in chapter 1, the IHCTP decision to work on a prefabricated roof system preceded the start of work on this thesis. A more complete explanation of this decision is contained in chapter 4.

The design goals stem from the earliest ideas of the IHCTP researchers; ideas that were gradually clarified, refined and solidified as time and study progressed. The characteristics focus on meeting consumer expectations, code issues and builder concerns and are based largely on competing favorably against the major competing system; conventional stick frame construction, either with rafters or trusses.

The goals are based on the constraints imposed by market forces and on actual physical factors. The market related issues include:

- Architectural design flexibility.
- Aesthetic requirements of finishes and details.
- Public perception of the system as influenced by the performance of earlier pre-fabrication building systems and methods.
- Market position: cost and quality in relation to competing systems.
- Structuring system advantages to benefit the party that decides which building system to use. This decision maker may be the owner or developer, designer or contractor.

The physical factors include:

- Ease of manufacture.
- Transportation size and weight limits.
- Erection size and weight limits.

• Construction time

• Compatibility with other building systems.

• Fire code compliance

• Thermal performance.

• Structural performance

• Preventing moisture and heat induced damage to the roof.

The system must equal or surpass minimum standards in these areas to be successful. Where applicable, an attempt is made to determine these standards quantitatively.

The market issues, physical factors and minimum standards combine to form a detailed problem statement. It is important to formulate this problem statement early in the design process as discussed in the evaluation of the design process, section 8.2. The design goals themselves are summarized in section 3.14.

3.1 Architectural design capabilities

The roof panel system is a pre-fabricated building system. One of the major complaints with pre-fabricated building systems over the years has been that they all look alike and lack individuality (section 3.4). This complaint has hindered wider acceptance of pre-fabricated building systems. It will be important for the panelized roof system to avoid this trap. This can be done on three levels; the overall forms, the finishes and the details. These are discussed in sections 3.1 and 3.2 and 3.3 respectively.

In the realm of forms, the system must be able to form the range of complex roof geometries that are used on common production built homes in the U.S. These include hips, turn gables, dormers, a range of slopes and spans and openings for skylights and other penetrations. In short, it should be able to do all things that a conventional rafter framed roof can do while imposing the fewest restrictions on the designer.

The system can accept some restrictions in terms of the flexibility of size and positioning of these elements. For example, the system must accommodate turn gables but it would be acceptable to constrain the width of the turn gable to a rib spacing multiple and to constrain its spacing such that its center-line falls on a panel to panel joint.

Extremely complex roofs incorporating many intersecting gables at varying slopes with turrets, cupolas, etc. are rare, especially in production built houses. Therefore, the capability to build these types of roofs is deemed to be unnecessary for this system.

3.2 Aesthetic requirements - finishes:

The interior and exterior finishes of the roof panels are an important consideration. Currently the standard finish on most houses is gypsum wall board, taped and painted on the inside ceiling surface, and asphalt shingles on the exterior roof surface. Other less common roofing materials are wood shakes, clay or concrete tiles, aluminum shingles and seamed metal sheets. For the interior, wood paneling and acoustic tiles are also used. As a basic guideline, a ceiling surface in a living area demands a high level finish whereas a semi-finished or unfinished surface is acceptable in an attic or other non-living area.

The finish strategy of the system will be governed by market acceptance. As it is very difficult to predict whether a new type of finish will or will not be accepted and it is unacceptable to restrict the choices of finishes available on the roof system, a semi-finished (suitable for painting) or unfinished (requiring drywall) should be the basic panel surface[1].

[1] Advisory board

3.3 Aesthetic requirements - details

The connection and joining details between materials and components is a good way to measure the quality of craftsmanship and construction in a house. Well thought out, good fitting and attractive details are an indication of quality construction and probable longevity of the work, and will be perceived as such in the marketplace. This is true for both interior and exterior finish details.

There should be a variety of ways to attractively detail the completed roof system to encourage individuality among dwellings as discussed in section 3.1. These ways should include the popular architectural styles that the market demands, perhaps utilizing pre-fabricated trim components. Preferably, the system will allow the designer or builder some latitude in detailing the trim. This can be done by providing a base to work from rather than a limited choice of pre-determined options (see 3.11 - compatibility). Likewise, the interior should support flexibility of choice in trim style and materials.

Homeowners place too great an importance on interior details for the their aesthetics to be compromised. The details should not reveal the nature of the roof system at first glance; that is, the technology should be transparent to the casual observer.

3.4 The public's perception of prefabricated construction

For the panel system to be successful, it will have to combat the public's longstanding negative perception of prefabricated construction. Negative perception was cited as the number one soft barrier to prefabricated construction in a 1988 survey of builders [Crowley, 88]. It connotes boring, repetitive design and shoddy workmanship in most American minds. The perception that prefabricated homes are shoddy and poorly built started after World War II. A major factor contributing to this perception was that pre-fabricated construction on a large scale was first attempted with low-cost housing. In this situation, the repetitive design and lower quality materials used was more a function of the low cost nature of the housing than of the prefabrication. In the ensuing years, the quality of construction and design of factory made houses has risen to, and above, the average site built conventional house. More recently, some manufacturers have begun to use the advantages of a controlled factory environment to make high quality, luxury homes. This has begun to change the public's perception, but there is a long way to go before pre-fabrication is associated with quality building.

A positive perception of prefabrication is prevalent in some foreign countries, particularly Japan and Scandinavia. In Japan, pre-fabrication started at the high end of the market with luxury dwellings. The ensuing association of pre-fabrication with high quality made consumer acceptance of pre-fabrication at the mid and low ends of the market much easier.

To combat the negative perception in the U.S., prefabricated building systems are often touted as using high quality materials and as being energy efficient. In addition to this, the panel system should be promoted as an alternative building component or product rather than as a prefabricated roof. Emphasis should be placed on the fact that the system plugs into other construction methods used in North America, Europe and Japan (section 3.11). Also, the importance of quality control and quality detailing is hightened as this system will be evaluated prejudicially by consumers and builders.

3.5 Market position of panel system

Currently, while there is wide regional variation, 65% of single family detached housing starts in the U.S. utilize roof trusses [LSI/F.W. Dodge, 88]. Most of the remainder use rafters. Costs of these systems depend on the degree of design complexity. The panel system is expected to be more cost competitive with rafters and trusses at the medium to high end of the design complexity scale.

Whereas rafters and trusses are highly sensitive to design complexity, the prefabricated panel system is expected to be less sensitive. The site work should be only slightly more difficult and the automated, flexible panel manufacturing process (section 3.7) will not be highly sensitive to varied panel shapes. Costs per square foot for rafter, truss and foam-core panel roofs are shown in figure 3.1 for simple roofs and complex roofs. Complex roofs include at least one turn gable and hip. Figure 3.1 compares these system's costs to a projection of what the panel system designed for the POC structure by the IHCTP may cost, based on materials and manufacturing cost predictions [Parent, 91]. Figure 3.2 shows cost broken down into material and labor for trusses, and seven types of roof forms built with rafters. If the panel system is significantly less expensive than rafters for the more complex designs, this should provide the panel system with an opportunity for early market acceptance.

Figure 3.4 illustrates the positions of truss and rafter roof systems and the potential position of the roof panel system with respect to five important factors. These five factors are major factors influencing the selection of competing building systems in the marketplace.

The panel system should be positioned in the market such that it is as close as possible to trusses in cost and significantly cheaper than rafters. This range is illustrated in figure 3.4. In this position, its advantage over trusses in the area of design flexibility will be apparent. The move from trusses to panels will be made to recover roof cavity space

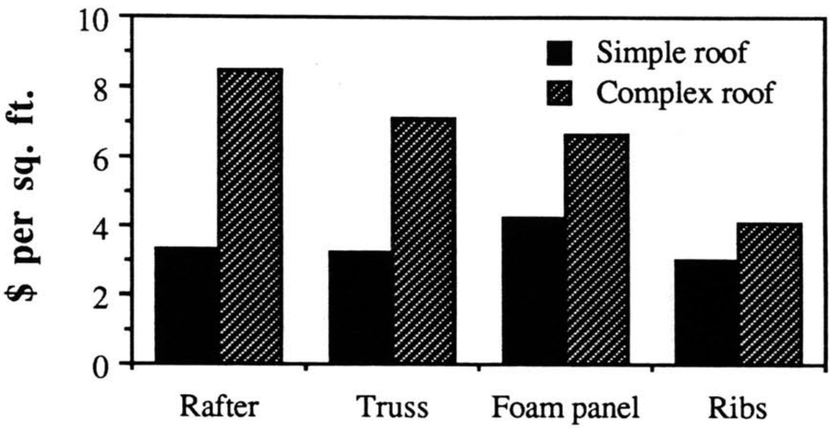

Figure 3.1 : Costs of four roof systems for simple and complex roofs
Source: [Parent, 91]

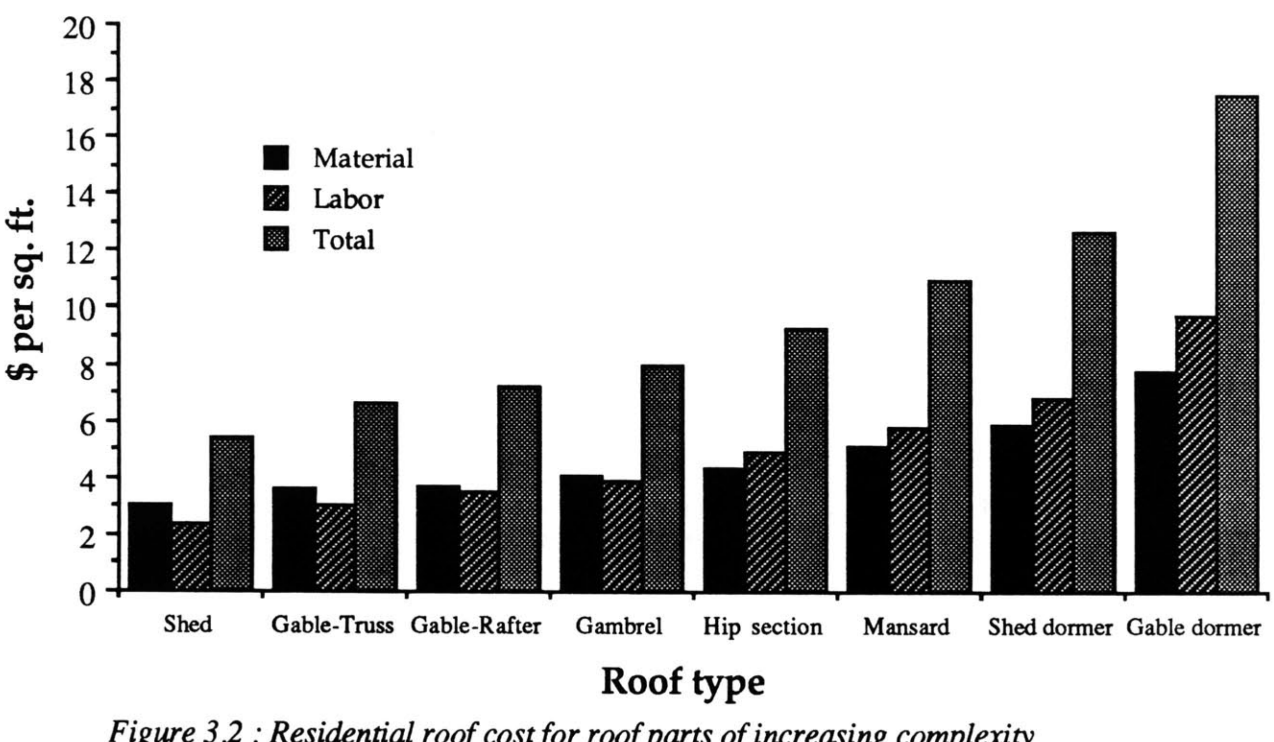

Figure 3.2 : Residential roof cost for roof parts of increasing complexity
Source: [R.S. Means, 1989], compiled by John Crowley

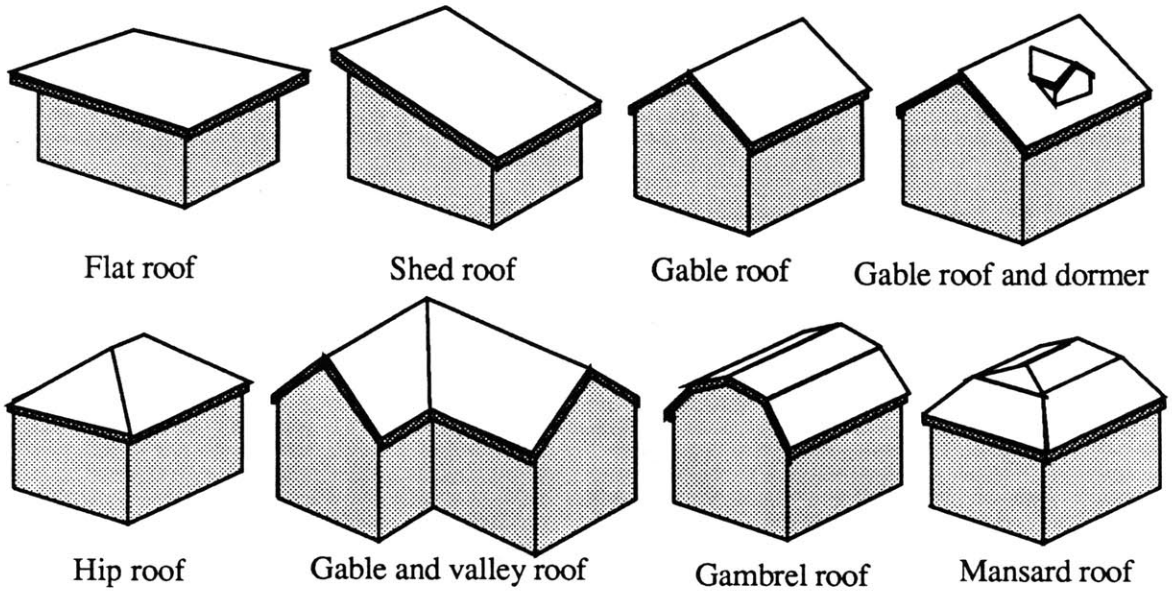

Figure 3.3 : Common roof forms

Factor	Low (good)..............................High (bad)
Design constraints	R ....P...T
Space use constraints	P........R..T
Construction skill level	P..............T..R
Construction time	P..T.................R
Construction cost	T..................P...R
P = panel system	**R** = rafter construction **T** = Truss construction

Figure 3.4 : Market position of competing roof systems (construction factors assume medium complexity)

and increase design flexibility with only a slight cost premium. The move from rafters to panels will be made for cost and time savings with a minimum sacrifice of design flexibility. Performance benefits will be realized in both moves.

3.6 Benefit to the decision maker

There are three principal players in the traditional home building process - the owner/developer, the designer and the builder. The designer is often eliminated as a separate player in the case of production built houses. Each player has different, and sometimes conflicting goals which stem from different motivating factors. The advantages of the roof panel system should be structured so the perceived benefits are most strongly directed at the player that will decide what building system to use for the roof. Of course in the long run, the end user should actually benefit.

The owner/developer is motivated most strongly by cost considerations and secondarily by quality and speed of construction. The designer is attracted to a system that delivers the best performance and design flexibility. The builder is motivated by convenience and construction speed. The owner/developer is usually the final decision maker but may be influenced in the selection of a building system by the designer and especially by the builder.

An example of a panel building system where the system advantages did not match the interests of the decision maker is that of Cheney Building System in New Berlin, Wisconsin. The panels in this system, called "Chase Thermo-Panels", used a cam lock fastener in the panel to panel joint (see figure 2.6). This method provided great convenience to the builder but did not translate into increased savings for the owner[2]. The Chase cam-lock panels are no longer made due to the prohibitive cost of the cam-locks.

The advantages of the panel system are to be structured to benefit the owner/developer by keeping costs low and improving performance. Also construction time will be kept down to further savings. The design goals are structured toward these ends.

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[2]Communication with Winter Panel Central (formerly Cheney Building Systems)

3.7 Manufacturing

One of the main reasons for prefabricated construction is to take advantage of manufacturing techniques possible in a controlled factory environment. The roof system components should be conducive to high volume production using "lean" manufacturing techniques. "Lean" manufacturing, in the context of the roof panel system, is a flexible technique using automation to minimize the inventory and line workers needed. This should enable quick response to orders - approximately 2-3 days from order to fabrication and shipping. For the short term solution, production machinery should use existing technology.

All roofs should be made to order. This lesson has been learned the hard way in the industry. Sterling-Homex is one example of a prefabricated homebuilder that was unable to carry their large inventory of homes, causing them to go out of business.

The level of capitalization possible, and hence automation, is determined by the plant's volume, which is a result of its market share and market area. Market share is determined by, among other things, price, which is strongly affected by the cost of production which in turn is determined by the manufacturing technology employed. This paradox is a major factor inhibiting the capitalization of housing component manufacturers. Therefore, the system should be able to begin manufacturing with a minimum of automation, adding more as market, and revenue, grow. This may be done by initially focussing sales at the high end of the market.

The limited market area of the roof panel plant is a result of the the limited delivery range possible with large, prefabricated building elements. A radius of approximately 350 miles may be the maximum range possible as explained below in section 3.8.

3.8 Transportation

In order to be transported along America's roads, the panel components are restricted to certain sizes. A truck trailer must fit within a specified envelope according to federal law. This envelope is 8'-6" wide by 13'-6" high by 53 feet long. A standard flatbed truck trailer rises 4 feet off the ground, leaving an envelope size of 8'-6" by 9'-6" by 53 feet for the cargo. There are provisions for transporting larger loads - up to 14 feet wide by 14 feet high by 60 feet long. These provisions vary from state to state and depend on the size of the load. State laws may restrict hours of travel for oversize loads (usually to daylight hours) or restrict the roads they may be driven over. Special permits, at about $50 per state and escort vehicles, at about $.85 per mile, may be required. Two escorts may be required for loads wider than 13 feet[3]. These restrictions and the variations between states can make interstate commerce in modular homes or other large items very complex. It would be costly to have a truck stopped at a state line because of some oversight, halted in a state when the sun goes down or forced to take a roundabout route over secondary roads. According to an Operation Breakthrough transportation study referring to truck shipment of building components, "Costs, associated with circuitous routing, increase directly with the additional mileage" [U.S. HUD, 75]. For these reasons; excessive cost, site accessibility and scheduling restrictions, it was deemed desirable to design a system whose components were transportable within the standard truck envelope.

In addition to the dimensional constraints to transportation posed by state and federal law, the market range of a factory is limited by the economics of transportation. Basic transportation costs for regular size loads are approximately $2.50 per loaded mile[4].

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[3]Communication with Home-Run Shipping Company
[4]ibid.

There is a quantum leap in the cost of transport from a one day to a two day round trip. The driver (and erection crew if included) must be paid overtime and put up in a hotel for the night, at about an additional $100 per driver[5]. Panel and modular home manufacturers have found that a plant can service a 300 to 350 mile radius if transporting oversize loads. This translates into a ten hour one way trip by truck, and one overnight stay. This limit was expressed by members of the advisory board and in an Operation Breakthrough Feedback report in the following quote: "Highway transport of modules as a general rule places the manufacturer in a non-competitive pricing position for distances over approximately 300 miles" [U.S. HUD, 75]. Transporting regular size loads that do not require special permits extends a plants range to about 500 miles. These limits apply to building panels as well as modules.

The transportation constraints, especially the range factor, make the location of the factory an important consideration. The factory should be within optimal range of the maximum number of future housing starts, which in itself is hard to predict. The limited market area of a factory results in a limited customer base which imparts a limit to the capitalization possible for a single plant (section 3.7). This has great implications for the manufacturing techniques that may be employed, which in turn affect the design of the system.

Separate from the shipping range issue, is the service range issue. Services provided by a component producer may include: design and engineering, construction consulting, financing, and warrantee services. The service aspect of the component business is very important and likely to grow more so in the future. The service range (or radius) of a local building component producer may pose even greater restrictions on the size of the distribution area.

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[5]ibid.

3.9 Erection

The roof panel components must be lifted onto the roof of a house during construction. This can be done either manually or with mechanical equipment (probably a crane). The manual strategy imposes severe weight and size limitations on the components. The maximum weight a two person team could be expected to lift and position on a roof is approximately 100 - 200 pounds. This manual strategy was abandoned since any meaningful component size would be impossible to handle. The crane needed for the erection of the roof panels would have to be readily available and inexpensive. Daily rental rates for the Boston area range from $500 to $700, including operator, for the cranes shown in figure 3.5, depending on size. The cranes are all truck mounted, hydraulic, boom cranes (figure 3.6).

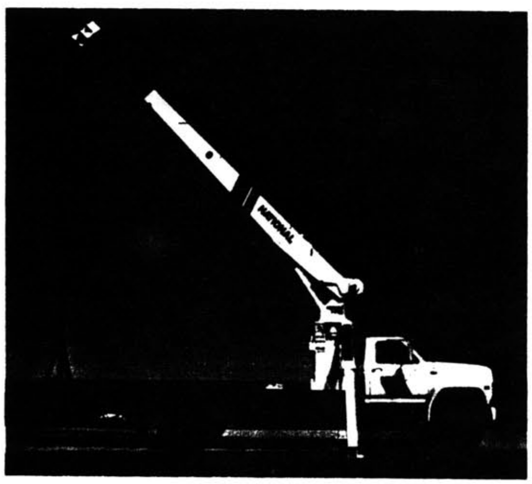

Figure 3.6 : Hydraulic boom crane mounted on flatbed truck
Source: National Crane Company product literature

A number of assumptions were made in order to establish erection criteria. Crane access to within 20 feet of one side of the house and a maximum house width of 30 feet were assumed. Based on these figures, an 8 ton crane would be appropriate for the panel

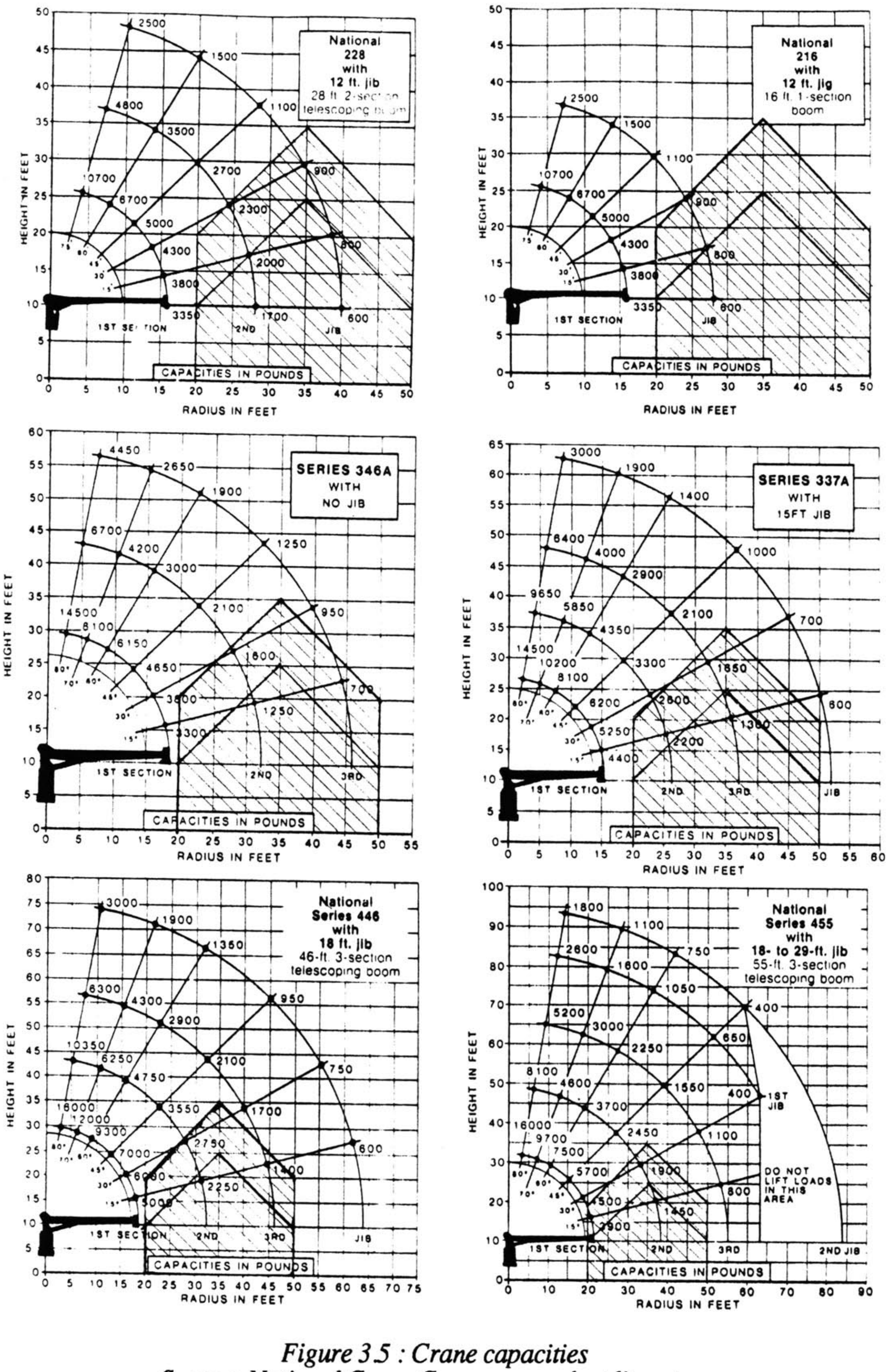

Figure 3.5 : Crane capacities
Source: National Crane Company product literature

system. This translates into a maximum panel weight of 600-700 pounds based on the reach capacities shown in figure 3.4. Adverse site conditions may entail the use of a larger crane at added expense.

In addition to being lifted up to the roof with a crane, the panel position must be fine-tuned in order for all joints to be fastened. Depending on the joint designs, the panel may need to be moved sideways a few inches to mate with adjoining panels. This maneuvering would most likely be done manually, implying a further weight constraint. Objects of many tons can be maneuvered while swinging from a crane as is done commonly in steel erection. However, once placed down, friction with the supports greatly reduces the weight that can be moved manually. For a two person team, 300 to 400 pounds is a reasonable limit. Panels weighing 250 to 300 pounds were successfully lifted and maneuvered into place in the lab and will be assembled on the proof-of-concept structure. Allowing the maneuverability criteria to control, a 400 pound limit was set as a design goal.

3.10 Construction time

From cost studies of housing construction, it is evident that the two major ways that a building system can impact housing costs is by increasing the speed of construction and by adding more value to components off-site. Time dependent costs of housing development, including; financing, marketing, management, overhead and general conditions; can be as much as 30% of total development costs (excluding land) for conventional construction. These soft costs, particularly construction financing and general conditions, can be drastically reduced by shortening the development time. A 50% reduction in these costs is not an unreasonable goal. Prefabrication is an excellent way to save time, and reducing development time is, in fact, the means by which prefabricated construction achieves most savings [Maxian, 89].

Speed of construction is also important for reasons of construction predictability, closing in of the weathertight shell, and enabling a builder to do more jobs per year with the same crew. Table 2.1 shows the construction times and crew sizes of various systems. Panelized construction greatly reduces the close-in time. It is not uncommon for walls, floors, and roof to go up in one day on a completely panelized house. For all but the most complex of roofs, a one day roof installation is a goal for the panel system. Limiting roof installation to one day is a major advantage since a dry day can be chosen and the house need not remain unsecured for an extended period. Material and equipment can be stored in the secure shell. The roof installer, whether the general contractor or a sub-contractor, only needs to make one trip to the site, and rent the necessary equipment for only one day.

Significant advantage is not gained by cutting installation time to half a day. The tighter the schedule becomes, the less room for flexibility and error. It is difficult to schedule other construction activities around the roof installation on the same day and, in all likelihood, the equipment would need to be available the whole day anyway since it is difficult to schedule construction precisely to the hour. It is of paramount importance, however, that the construction be comfortably completed on the specified day, with no risk of requiring the expensive equipment to return to the site.

3.11 Compatibility with conventional construction

From early on, compatibility with conventional construction was recognized as an important feature of any new building system for residential construction. One of the lessons most strongly learned in the twentieth century's numerous attempts at developing new construction systems is that open systems are far more successful than closed systems. Open systems[6] are systems that are compatible with other construction systems and can accept input from them at varying points. An example of a closed building system that failed is the precast concrete building system once used extensively for apartment buildings in Eastern Europe. This system failed because each step in the process was dependent on the previous one. One broken link and the entire chain fails. In an open system, some other construction method could replace the broken link.

In the case of U.S. residential construction, compatibility with stick frame construction is important for the panel system. Three compelling reasons, in addition to that mentioned above, illustrate the need for compatibility. First is the construction of complex roof parts not included in the roof panel system's capabilities. While these parts (complex dormers, turrets, cupolas, etc.) may eventually be available as components, compatibility would allow the builder to frame them conventionally and tie them into the otherwise panelized structure. The second reason is that the designer may want to break with the modular dimension restrictions of the system. Any non-modular dimensions can be infilled with conventional construction to bring the panel portion of the roof into accordance with the modularity. The third reason for compatibility is to allow for the eventuality of future work on the house. Future homeowners would not want to be dependent on being able to acquire matching panels 10 or 100 years down the road. They can rest easy in the knowledge that future work can be done with conventional stick framing if necessary.

[6]Open systems here means 'Technically', or physically, open systems as opposed to commercially open.

3.12 Code compliance

The roof panel system must meet all building code regulations in order to get built. There are three main code bodies in the U.S. - the UBC, SBCCI, and BOCA. The areas of the codes that affect the roof system most are fire, structure and insulation.

Difficulties with code approval and with acquiring a local building permit can be very costly and time consuming - to the point of negating any advantages gained by the panel building system. Problems with national and local codes were identified as having the largest cost impact of all hard barriers to prefabricated construction in a 1988 survey of home builders [Crowley, 88]. Therefore, the roof panel system must clearly meet or surpass these minimum code standards.

3.12.1 Fire performance

Roof and ceiling assemblies for single family dwellings are typically not required to have a fire rating. However, the interior face of the roof panels (the ceiling) must have a 15 minute fire rating in the case of a plastic foam core panel. This can be achieved with one layer of 1/2" type "X" gypsum wall board. Fire ratings are determined by the ASTM E-119 test. Also, the roofing material may need to be rated for flame spread. There is a trend by the regulatory agencies and the market toward more stringent standards in this regard [Tonyan, 91]. For this reason, a one hour fire rating for the roof assembly would be desirable.

3.12.2 Structural performance

The UBC (1988) code defines the maximum deflection for roofs as L/240, where L is the span in inches, or L/180 where a brittle skin material such as plaster is not being supported. A ground snow load of 40 psf and a wind load of 33.8 psf (equivalent to a 90 mph wind) were selected as being adequate for covering the majority of building markets in the U.S., and therefore adequate for the roof system design load. For a more detailed discussion, see Kucirka, 1989 p. 77 or the code books.

In addition, the code stipulates that for concentrated loads, the panel must be able to withstand 42 psi over an area of 7.14 square inches, e.g. the footfall of a worker [ICBO, 88].

3.12.3 Insulation - thermal performance

The thermal resistance of a wall, roof or other building part assembly is described by its "R" value. The thermal resistance of an insulation or other material is usually quoted for a one inch thickness of the material. This is its R-value per inch. R-value has units of ft^2 - °F-hr/Btu which is simply the inverse of conductivity k (Btu/ft^2 - °F-hr).

In conventional roof construction, overall calculated R-values commonly range from 20 to as high as 60. It is important to note however, that these calculated values often bear little resemblance to the actual performance values after installation. Numerous factors work to reduce the actual R-value of a stick-built wall or roof well below its theoretical value. These factors include: insulation voids, thermal bridges, air leaks, air and moisture intrusion and convective loops. They result from both sloppy installation and the inherent nature of the stick frame and can work to reduce the actual R-value of a building envelope by as much as 30%. Thermal bridging alone, caused by the 2x wood framing, in a wall insulated with R-19 fiberglass batts can reduce the insulative value by 24% to R-14.4 [Nisson, 85]. These factors are typically not addressed in conventional construction. Advertising and promotional literature for these homes usually quotes the value calculated by simply multiplying the R-value per inch of the insulation material by its thickness.

In a manufactured building component such as a roof panel, the actual R-value for the entire component would be evaluated. This value would translate directly into the envelope value since the panel would not be significantly succeptable to sloppy installation affecting the thermal performance.

An R-value of 30 was chosen as a target for the actual insulative value of the roof system. This number was based on input from the advisory board and guidance from the building codes. The CABO Model Energy Code (1983 edition) establishes model R-values based on climate of a region. These values range from 20 to 40. A value of R-30 meets or exceeds the CABO requirement for most building markets in the U.S. [Tonyan, 91]. This includes the swath of territory running across the country bounded on the north and south by Massachusetts and the Carolinas. Modifications to the insulation could be made for regions experiencing more extreme temperatures.

3.13 Preventing moisture and heat induced damage to the roof: ventilation of the roof surface

Most conventionally built houses have vented roofs. Venting the roof surface serves two main purposes: to cool the roofing material and to remove moisture. It is important to keep down the temperature of the roofing material since many roofing materials degrade faster at high temperatures. This is done by circulating air underneath the roof sheathing. The other purpose is to prevent moisture problems by carrying out water vapor with the circulated air. Moisture problems include condensation, degradation of the insulation and finish materials, and rotting of structural members and sheathing.

Venting of the roof surface is complicated with the use of insulated envelope panels. Until recently, most foam core roof panel systems were not vented and some moisture problems at the joints have been observed. Conventional construction, in the case of an insulated roof cavity, incorporates an airspace between the under side of the roof sheathing and the top of the insulation (figure 3.7). In the case of an uninsulated attic, the insulation is on the attic floor and the entire attic space is vented. The insulated roof cavity case incorporates eave and ridge vents to facilitate the circulation of air through the airspace.

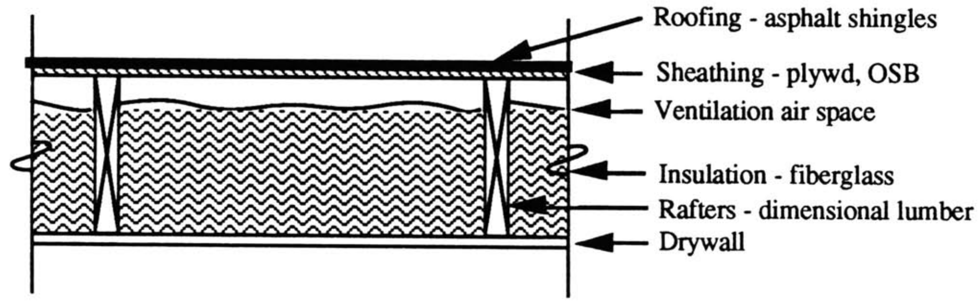

Figure 3.7 : Ventilation in a conventional rafter-framed roof

Some roof shingle manufacturers void the warrantees on shingles installed over non-vented roofs [Toole, 90]. This reflects a concern that overheating of the shingles under a hot sun may reduce the lifetime of the shingles. While this concern exists, it is unknown whether there is actually a technical problem here since conclusive studies have not yet been done.

It was decided that a completely vented roof panel system would be an important design goal. This includes venting at hips, valleys, and other complex roof parts; which is difficult even with conventional construction. Two-way venting (e.g. air movement across rafters in conventional framing) was stressed as being very important by the advisory board. This would allow for the insertion of discontinuities (skylights, etc.) that could interrupt one-way eave-to-ridge venting (figure 3.8).

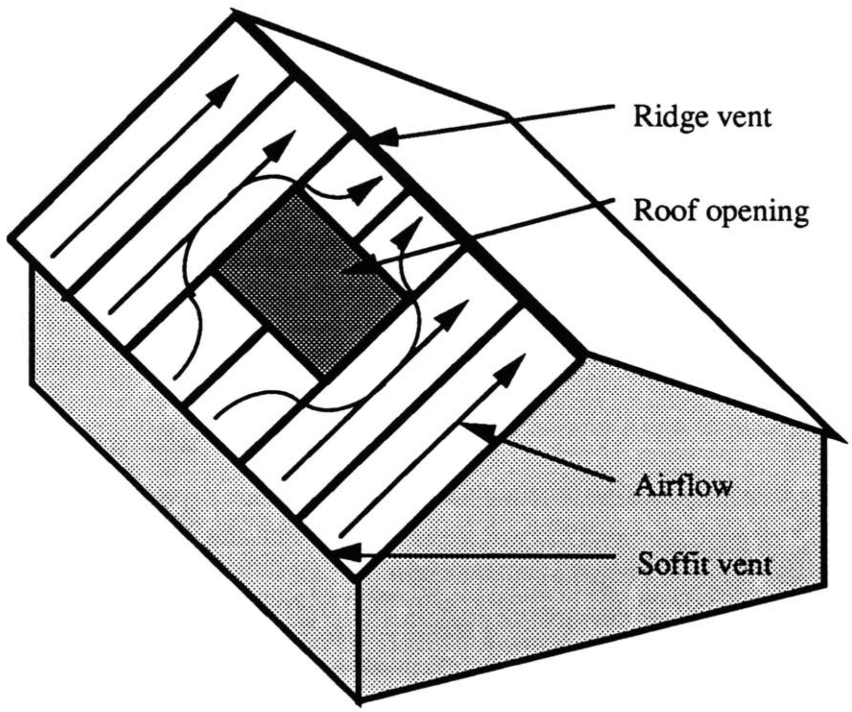

Figure 3.8 : Two-way venting to accommodate roof openings, etc.

3.14 Summary of design goals

Market issues:

1. The system should be capable of constructing that which the conventional production built home market demands - i.e. hips, turn gables, dormers, etc.
2. The system should allow a variety of market acceptable choices for the finish materials.
3. The system should allow a variety of market acceptable choices for the detailing.

4. Strict quality control and good design must be maintained in order to overcome the negative perception of prefabricated house systems.

5.The system should be situated in market such that its cost approaches that of trusses and its flexibility is closer to that of rafters.

6. The perceived advantages of the system should be structured to benefit the party who selects the system to use.

Physical constraints:

7. Ease of manufacture, production on demand (with minimum lead time), flexible manufacture, and ease of customization should be achieved with a minimum of capital investment consistent with the market share and market radius of the plant.

8. The dimensions of the components should fit within the standard truck envelope.

9. The dimensions of the components must fit within the crane capacity limits and manual maneuverability limits. The erection crew should be no larger than conventional homebuilding crews and should not need to be highly skilled.

10. A roof of reasonable size and complexity roof should go up and be weathertight in one day.

11. A builder should be able to tie rafter construction into the panel system.

12. All code regulations must be met, including those pertaining to:

    Fire

    Structure

    Insulation

13. The roof surface should be vented.

CHAPTER 4 Design decisions

4.1 The decision tree

In order to make the general case for the feasibility of a panelized roof system, we must undertake to design such a system, build it, and demonstrate its feasibility. The paradox here is that in order to prove the general case, a specific design must be developed. An important measure in making this case is to keep a record of the development of the system; to understand what decisions were made at what points in the process and for what reasons.

These decisions are numerous and complex. The shape and size of the panels, the method of support and the nature of those supports, the materials and their configuration within the panel, the way the panels are joined together, and the question of the interior and exterior finish surfaces must be addressed. These many choices lend themselves to the analogy of a tree of decisions. The decision tree is illustrated in figure 4.1 as a series of 12 hierarchal levels of decisions progressing from the general to the more specific. Each level addresses its corresponding issue from the following list:

1. Type of housing
2. Part of house to focus on
3. Part of shell to focus on
4. Innovation strategy
5. Panel section type
6. Panel core geometry
7. Material selection
8. Roof structural strategy

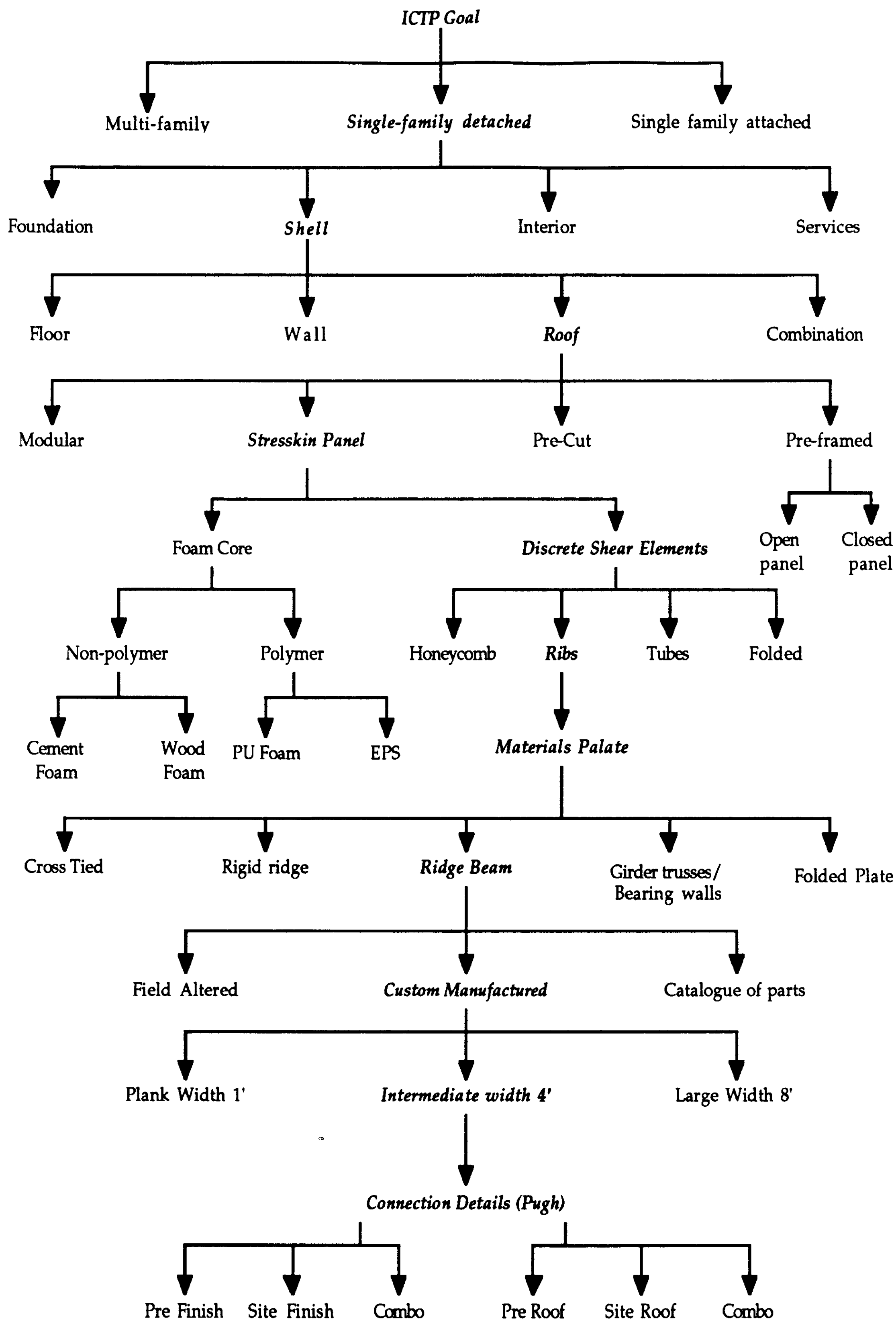

Figure 4.1 : The decision Tree

9. Manufacturing strategy

10. Panel geometry (width)

11. Connection system design

12. Finish strategy

The decision tree is an attempt to organize the series of strategic and design questions addressed throughout the course of the roof system design project.

The tree analogy does have its limitations however. The diagram in figure 4.1 is deceptively simple. It is not meant to imply that the decisions were made strictly in the particular sequence shown, arriving directly at the final design. The overall trend of general to more specific issues was followed, but no design process is so simple.

Many issues were investigated simultaneously and there was constant looping back and forth between levels of decisions (this is central to good design). The reversal of decisions was not uncommon. Questions of materials were addressed from the beginning (as they must be), and some of the decisions in the lower half do not depend strongly on those made in the upper half. Many lower decisions may have applicability for other cases as well. The hierarchy of the decision tree diagram most closely reflects the order in which final decisions about the panel system design were made and illustrates the most efficient and ideal path through the network of decisions. Realistically, however, it can never be followed since the designer does not know what the tree looks like in the beginning. The explanation of the decision process and issues at each level of the tree remains valid, despite these complications with the whole of the tree.

The tree diagram is best used as a tool for understanding what has gone on in the design process; to untangle the complicated web of decisions and asses their appropriateness and thereby the appropriateness of the design reached. It also serves to illustrate the general case by depicting the decisions alongside a partial list of alternatives. Other design solutions are possible by taking different paths down the tree. Some of these other paths will be explored to a lesser degree - thereby further illustrating the validity of the general case of panelized roof construction.

4.1.1 What type of housing? - Single family detached.

To own a single family detached (SFD) home is the goal of many Americans. This "American dream" is very strong and is likely to remain so for quite some time.

Statistics support this assertion. In 1987 all products and construction associated with new residential construction in the U.S. was $194,772,000,000. New starts included 1,024,400 single family detached homes valued at $114,463,000,000 [U.S. DOC, 89]. This is 59% of the total value, making it the largest category of housing starts in terms of number of starts and total dollar value.

In addition to the above market reasons, the selection of SFDs is attractive for design purposes. The choice of single family homes as the design subject simplifies the design problem by reducing the number of design variables in terms of form permutations. Transferability to other housing types and to light commercial construction is still possible and is the intent of the IHCTP.

4.1.2 Why the building shell?

An examination of the cost breakdown for stick-frame construction of single family dwellings (table 2.1), reveals where innovation has the largest potential to impact costs. Framing costs range from 20% to 25% of construction costs, and the exterior walls, which include the sheathing, siding, insulation, windows and trim, represent 8% to 17%. These two, plus interior drywall, comprise the building shell (or envelope) which totals 30% to 40% of the building's construction cost.

Much of the materials and techniques used in the stick-frame construction of the envelope are relatively primitive and labor intensive. This is particularly true of the framing and drywall. A potential exists to replace this complicated assembly of parts in the shell with engineered products containing a higher level of finish.

4.1.3 Why *roof* panels?

The roof can be defined as a single building subsystem. This allows detailed study of an individual system while recognizing that it must be integrated into the whole building. The roof has a simple, yet demanding program - to keep the weather out. There are usually a minimum of services and utilities to be integrated into it. The highest structural, thermal and environmental requirements of a house are to be found in the roof. Prefabricated panels may have the greatest potential for improvement over conventional construction under these conditions. The roof poses the most complex geometrical and structural challenges and is consequently the most difficult part of the house to frame conventionally (figure 4.2). The roof is the final and most crucial step on the critical path to getting the house weathertight and therefore increased speed of its construction is greatly beneficial. Improving the technology of roof systems is a specific need that has been identified by builders in the marketplace[1].

There are many panelized wall systems on the market, but few systems which include the floors and roofs. Few foam-core stresskin panels made, are capable of spanning the long distances required of floors and roofs without intermediate support

[1] Advisory Board

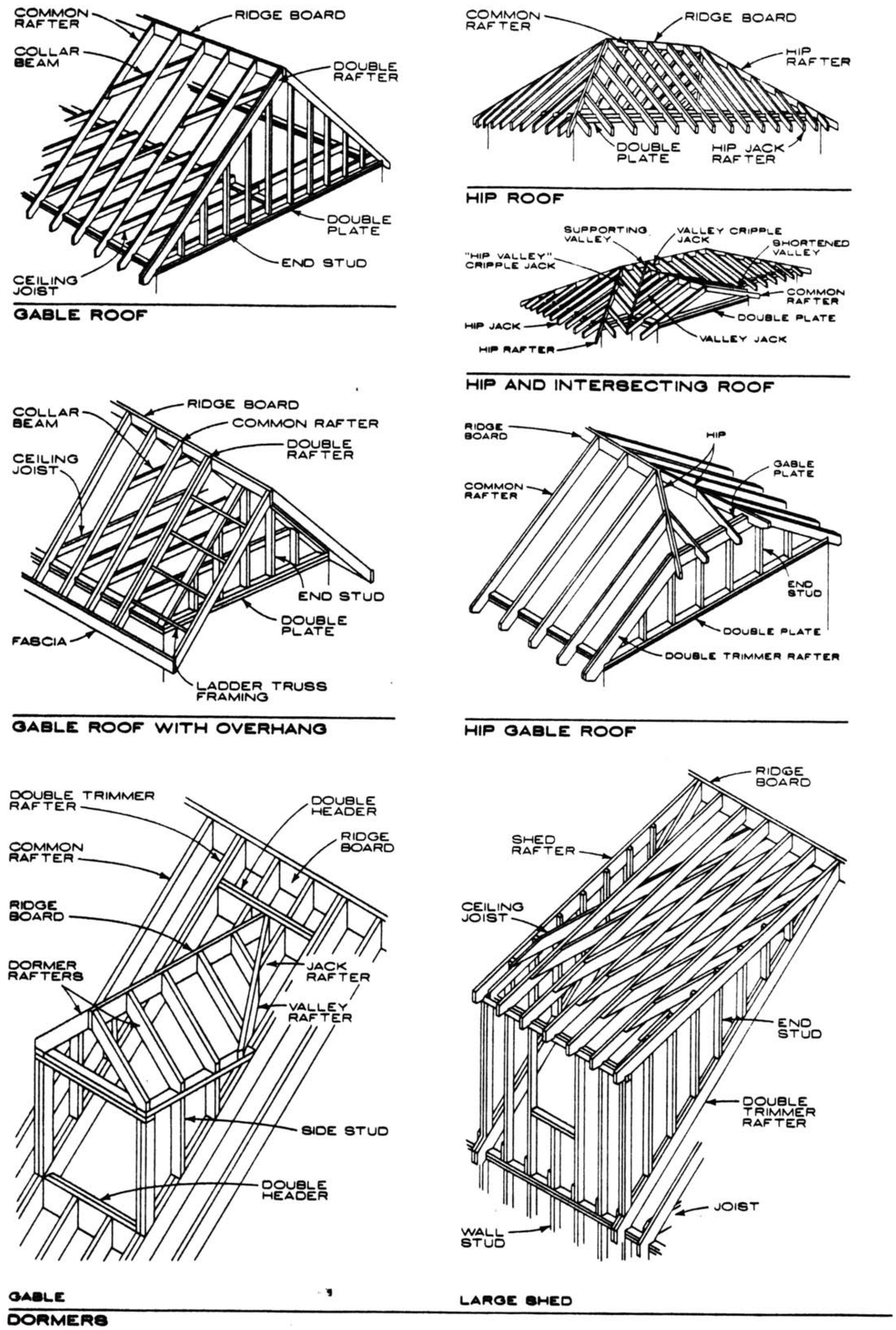

Figure 4.2 : Conventional roof framing
Source: [Ramsey/Sleeper, 81]

Finally, the roof technology may be transferrable to floor and wall systems, allowing that utilities pose new challenges.

4.1.4 Stressed skin panels

This level of the decision tree deals with the method, or strategy of innovation that the IHCTP takes in the attempt to meet its goals within the context of a roof system. The alternatives, as explained in section 2.2, include modular construction, pre-framed panels, pre-cut construction and stresskin panels. Stresskin panels were selected as the means for the construction of the prefabricated roof system.

Modular construction, as commonly practiced, does not mesh with the strategy of componentization that the IHCTP has embraced. This strategy is to gather the highest value-added portions of a building into a component that can be manufactured using advanced techniques and shipped efficiently, while retaining overall design flexibility. The modular strategy is further limited by the focus on roof construction, an area where modular construction runs into difficulties. To combat the major problem of modular construction; that of low mass to volume ratio in shipping, the roof is built sometimes by using folding-out roofs or by using conventional roof trusses on top of the modules. Modular construction may be innapropriate in the context of componentization, however, stresskin panels, and the materials being investigated by the IHCTP, may be applicable to modular construction.

The goal of the IHCTP is to *significantly* improve the quality and affordability of housing. This precludes the use of the pre-framed panel strategy. This type of panel merely relocates conventional materials assembly to the factory. The increased systemization and automation allowed by this has been a longstanding goal of panelizers. It is unlikely that the IHCTP could improve on this significantly enough to meet its goals.

Historically, most major building innovations have been achieved through the use of new materials. The IHCTP is investigating a number of new building materials primarily for use in building components. These new materials will demand a new method of assembly and would not necessarily be compatible with pre-framed panel production.

Pre-cut construction, as mentioned in section 2.2, involves very little prefabrication. It usually is little different from conventional stick frame construction and is used mainly on very expensive homes. For these reasons it was not seen as a good model for the roof system innovation strategy.

Given the goals of the IHCTP, stresskin panels are ideally suited for use as a strategy for innovation in the design of the roof system, . They are structurally efficient in their use of materials, and therefore are lightweight and capable of spanning the long distances required of roofs. The core and skin materials being investigated by the IHCTP (cement foam and OSB) are well suited for use in stresskin panels. Because of the unified structural unit that stresskin panels present, they are likely to be more robust in resisting shipping and erection stresses than conventionally assembled materials. Stresskin panels can be integrated into the trend of componentization of housing construction.

4.1.5 Discrete shear elements in the core

To meet the near term IHCTP goals, materials that are either on the market presently or on their way to market were needed. Materials that are still in the research phase - such as lightweight cement foam or corrugated OSB - or materials that are still theoretical - such as wood foam - may be appropriate for the intermediate and long term time frames. For the near term however, it was necessary that the material's mechanical properties be established with some confidence and that a method for large scale manufacture of the material at reasonable cost be known. It was not necessary that the material currently be in large scale production.

Kucirka has developed a program to design a sandwich panel for a single bay residential roof [Kucirka, 89]. It can design a panel that simply spans from eave to ridge in beam action (figure 4.3), or is in a folded plate configuration. In the simple-span case, panels are assumed to be structurally independent and loads between panels are not considered. The program optimizes the panel with respect to cost and given a specified R-value, material properties, geometry and loading. The program was applied to many combinations of face and core materials in order to determine their potential for use in structural sandwich roof panels. Table 4.1 shows the design configuration and constraints used for the input values and table 4.2 shows the combinations of materials and the results they yielded. These results are compared to a ribbed panel system[2]. None of the foam-core sandwich panel configurations appear better than the results possible with an engineered ribbed panel system.

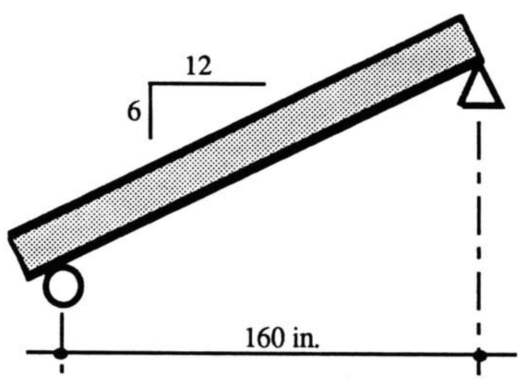

Figure 4.3 : Roof panel configuration for Kucirka program

In addition to this rough evaluation, it is worth exploring in more detail why polymer foams, in particular, were not selected for the panel system design in the near term. According to the technical and availability requirements stated above, the only

[2]A transformed section was used to simulate a ribbed panel with the Kucirka program.

Table 4.1 : Kucirka Program input parameters

Horizontal distance between eave lines	320 in. (26'-8")
Slope of roof	6 in 12
Live load per horizontal projected area of roof	40 psf
Wind pressure normal to roof	33.8 psf
Allowable deflection for live only; dead + live load	240/l; 180/l
Interior-exterior temp difference for max. summer/ appropriate winter/max. winter	100/70/100 F
Required R value for panel	30
Maximum core depth considered	16 in.
Weight of roofing material	2 psf
Weight of interior finish material	2 psf

feasible foam core materials available are polymer foams. Presently no other foam core materials meet the performance requirements satisfactorily.

There are two main drawbacks of polymer foams that resulted in their poor evaluation using Kucirka's program and which led to the decision to go with discrete shear elements. These are concerns over the possibility of long term creep deflection and cost. The two most likely polymer foam candidates (and the two most commonly used in building construction) are expanded polystyrene (EPS) and urethane foam (PU) (see section 2.3). All polymer materials, and many other materials to a lesser degree, when under continuous loading are subject to creep. Creep is the irreversible time-dependent deformation of a material under continuous loading. Roof panels have a horizontal span component and therefore are subject continuously to some bending load.

The long term effects of creep on a long spanning panel (over 12 feet) such as the one in the roof system design are not fully understood. To date, there is no data to support the viability or the non-viability of polymer foam core panels in supporting load continuously without permanent deformation. Foam-core panels have not been observed to have excessive creep problems in the field, but they are not currently used for spans over 12 feet without intermediate support.

Table 4.2 : Kucirka Program results

Materials	Core depth (in.)	Face thick. (in.)	Weight (psf) N/I finishes	R value	Ext. Insul. thick. (in.)*	Material cost of panel ($/sf)
Urethane with:						
Steel.	10	.016	2.84	77		**2.19**
Aluminum	14	.017	2.8	108		**3.18**
OSB	9	.5	4.83	70.4		**2.21**
O/I hi dens.**	8	.346	10	61.7		**8.01**
O/I low dens.**	12	.269	5.36	92.7		**4.80**
Fib. Re. Gyp.	9.5	.273	5.95	73.4		**3.99**
Wood Foam @ 2 pcf with*:**						
Steel.	12	.014	3.03	60		**1.25**
Aluminum	17	.01	3.11	85		**1.72**
OSB	12	.271	3.81	60.6		**1.27**
O/I hi dens.**	10	.3	9.2	50.1		**6.45**
O/I low dens.**	13.5	.296	5.95	67.8		**3.90**
Fib. Re. Gyp.	11	.331	7.1	55.3		**3.56**
Cement foam @ 10 pcf with:						
OSB	10	.25	10.2	30		**1.48**
OSB + ext. PU*	7.5	.278	8.4	30.3	2	**1.56**
Cement foam @ 20 pcf with:						
OSB	15	.25	25.6	30		**3.79**
OSB + ext. PU*	4.5	.531	11.6	30.4	3.1	**2.20**
OSB Ribs	9.5	.438	5.65	31	9****	**1.17**

* Some material combinations include non-structural urethane exterior insulation to increase the R-value of the panel when additional structural core material would be superfluous.
** O/I is an organic/inorganic composite of cement and wood fibers at two densities.
*** Wood foam is a theoretical material that has not been produced in the lab. Properties are based on projections from the solid material [Tonyan, 91].
**** In the ribbed panel case, the additional insulation is loose fiberglass placed within the core of the panel

Although creep is a concern, high cost alone would have been reason enough not to use polymer foams for the roof panel system. Table 4.3 shows the cost for candidate polymer foams per board foot. Table 4.5 compares the cost per insulative value (R-value) and per Young's modulus (E) of these polymer foams and of non-structural insulation and structural wood materials. While the polymer foams are the only materials that possess good properties in both the structural and insulating categories (with the possible exception of cement foam), they are less cost efficient than materials that specialize in either of these categories. As seen in table 4.2, the thickness required for structure is outrageously expensive and the resulting R-value is overkill. Also, being tied to the price of oil, the price of polymer foam is very unstable.

The use of polymer foam cores in building panels can therefore be justified only if they bring other advantages to the system that offset increased materials cost. In fact, they bring advantages in manufacturing, site assembly and performance. The three layer sandwich assembly is simple to manufacture and provides simple site construction methods. Performance benefits include the high impermeability of the polymers eliminating the need for a separate vapor barrier and resulting in a very "tight" house - with little heat loss due to infiltration.

The design team believed that it was possible to get these same advantages using other materials. We would have to develop manufacturing and site construction systems that would be comparable in efficiency to the polymer sandwich panel and spline connector systems. These other materials would be more cost efficient in the task they were each being asked to do.

Table 4.3 : Properties of candidate core and insulating materials

Core Material	**E ksi**	**G ksi**	**Shear**	**Density lbs/c.f.**	**R/inch**	**Cost $/b.f.***
PU foam	1.5	.7	.033	2	6-7.8	.19
EPS	.6	.24	.02	2	4	.12
Paper honeycomb	60	10	.125	3.8	.23	.23
Alum honeycomb	90	20	.130	3.6	0	3.60
Cement foam @ 10pcf**	1.146	.458	.02	10	1.91	.12
Cement foam @ 20pcf**	9.17	3.67	.02	20	1.18	.25
Fiberglass Batt Insul.	-	-	-	1.5-2.5	3.2	.05
Loose fiberglass	-	-	-	.6-2.5	3.2	.03
Rock wool	-	-	-	1.5-2.5	3.1	.03
Cellulose	-	-	-	2.2-3	3.2	.04
Perlite	-	-	-	2-11	2.7	.10

*b.f. is a board-foot, or 1/12 of a cubic foot at the density shown.
** Theoretical properties based on projections from the solid material.

Table 4.4 : Properties of candidate face materials

Face Material	E ksi	Therm x 10-6	Tensile Str.	Density lbs/c.f.	R/inch	Cost $/b.f.*
Steel	29,000	6	30	440	.003	9.167
Aluminum	10,000	13	22	165	.0007	15.26
OSB	850	5	.95	40	1.11	.5
Plywood	1,700	3	1.7	36	1.25	.525
Hardboard	300	?	?	50	?	1.2
Fiber Reinf. Gyp.	2200	6.8	2	96	.417	4
Eterboard**	2080	6.8	1.38	96	.42	5.3

*b.f. is a board-foot, or 1/12 of a cubic foot at the density shown.
Eterboard is a wood fiber cement composite board.

Table 4.5 : Moduli and Insulating value per dollar per board-foot for Candidate Materials

Material	Young's Modulus (E) per $/b.f*	R-value/inch per $/b.f*
PU @ 2 pcf	8	37
EPS @ 2 pcf	5	33
Fiberglass, batt	-	64
Fiberglass, loose	-	107
Rock wool	-	103
Cellulose	-	80
Perlite	-	27
Cement foam @ 10pcf	10	16
OSB	1700	2
Plywood	3238	2
Steel	3164	-
Aluminum	655	-

*b.f. is a board-foot, or 1/12 of a cubic foot at the density shown.

An additional, and significant, advantage of discrete shear elements for the panel core is the ease of panel venting (section 3.13) with this type of panel. Venting of the roof surface is potentially much simpler in a panel core in where air can circulate above the insulation and between the shear elements.

The specialized materials in this type of panel would be configured into structural shear elements and a separate insulating material in the core of the panel. The complete prefabricated component would have the same or better qualities at a lower cost.

4.1.6 Ribs

Under the heading "Discrete Shear Elements" come a number of possible design solutions. Those considered include honeycombs (both metal and paper), tubes (cardboard), ribs or webs, folded and corrugated geometries (figure 4.4). All of these designs incorporate some members to hold the faces of the panel apart and to transfer shear stresses between them. Non-structural insulation fills the cavities between the members and is generally not affected by the configuration of these members, except for purposes of manufacture. One major consideration with discreet shear elements is the degree of thermal bridging they will induce across the panel. Table 4.6 compares approximations of the cross sectional areas of solid material available to conduct heat across the panel for the 5 types of panels and 2 types of rafter framing. Assuming similar materials (wood fiber based products), this can be used as a first approximation of the rate of heat transfer. As can be seen, most of the designs provide less area than conventional framing.

Honeycomb: Honeycomb can be treated similarly to a polymer foam core in terms of manufacture and even site construction. A honeycomb panel is assembled in a three layer sandwich with the additional step of adding insulation within the honeycomb cavities. Disadvantages of this core are the high cost of both paper and metal honeycomb (table 4.4) and the significant thermal bridging that occurs across this type of panel (table 4.6). Thermal bridging is more severe in a honeycomb because the large number of closely spaced pathways enable heat to move directly through the panel without having to first travel along the face to the location of a bridge.

Tubes: Cardboard tubes are made in large quantities for textile and paper roll cores and for concrete formwork. Using similar tubes in the core of sandwich panels was considered. They would provide manufacturing advantages (tubes roll and would self align in the panel) and were thought to be relatively cheap. This concept was dropped because tubes are neither structurally efficient - especially in the core of a sandwich panel since circular sections are not good shear webs, nor are they so cheap.

Folded: This concept includes a number of designs. They have in common one material that acts as the core and face simultaneously by altering its geometry throughout the panel. One version of this panel is the corrugated panel. The material for this panel would be corrugated OSB. Research on this material continues at a number of locations but its cost and large scale manufacturing issues are not understood well enough yet to be considered for the near term design solution. Another version is a panel face material that is folded back on itself such that a continuous sheet of material forms both the faces and the shear-transferring core elements. This material would be some sort of cardboard. Samples of this design were built using "Thermo-Ply", a cardboard based sheathing material. Manufacturing difficulties were cited as reasons for abandoning this concept. The machine to do the folding would be very complex and costly and the rate of production would be in all likelihood, very slow. The manufacturing line would need to be as wide as the length of the longest panel to be built. This would call for a folding machine over twenty feet wide. There would be much manufacturing waste when the panels are cut to length or cut on

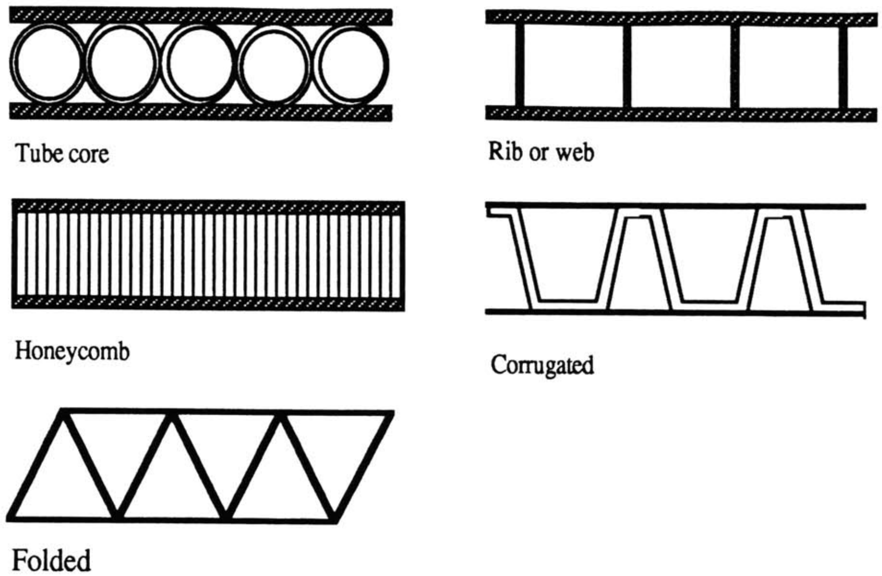

Figure 4.4 : Panel core sections

Table 4.6 : Thermal bridging cross sectional area of discreet shear element panels

Type	**Assumed geometry for 48 in. wide panel**	**Cross sectional area in sq. in.**
Honeycomb	1/32" x 1 per in. x 2 directions.	3
Tubes	5 tubes x 2 sides x 1/4" thick walls	2-1/2
Folded	17 folds x 1/8"	2-1/8
Corrugated	8 corrugations. (@ 6" o.c.) x 1/2" thick	4
Ribs	4 ribs x 1/2" thick	2
Conventional rafters 16" o.c.	3 rafters @ 1-1/2" thick	4-1/2
Conventional rafters 24" o.c.	2 rafters @ 1-1/2" thick	3

angles as compared to a continuous line running lengthwise. Increased panel width allowed by this manufacturing system is not an advantage due to shipping constraints.

Ribs: On the surface, a rib panel seems very similar to conventional rafter construction - thin members on edge run the length of the span and are covered by sheathing. However, the rafters in conventional construction are designed to act as beams carrying bending loads, with sheathing contributing to the overall in-plane shear stiffness of the roof, but playing no significant role in resisting bending. The ribs in a stresskin panel are designed to carry only shear and to engage the faces to carry tension and compression (section 2.3).

Just as the shortest path between two points is a straight line, the most efficient transfer of shear across a sandwich panel is a straight rib. Therefore, a rib panel is the most efficient use of material for structure. Table 4.6 shows that ribs have the potential to minimize thermal bridging. Also, for a rib panel, there are many possible materials to use, many of them inexpensive and the obstacles to manufacturing are not insurmountable, the primary one being the rib-face connection.

4.1.7 Materials

Sections 4.1.5 and 4.1.6 detail the path that led to a ribbed panel. The ribbed panel system requires two basic classes of materials: a dense, rigid material for the two faces and ribs, and a non-structural insulation material to fill the cavities between the ribs. There are many possibilities for both of these applications. Face materials considered include steel, aluminum, cement fiberboard, plastics, fiber reinforced gypsum board, and many wood fiber based materials such as plywood, waferboard, OSB, hardboard and cardboard.

Metals are not as appropriate for ribbed panels as they may be for foam core panels. Faces in foam-core panels are continuously supported by the rigid foam. In a ribbed panel they would need to be very thick, and therefore heavy and costly, to resist local inter-rib deflections. Also, metal faces increase two dimensional heat transfer, facilitating the movement of heat to the rib locations and then across the panel. Cement fiberboard is too heavy and too expensive (tables 4.2 and 4.5). Plastics are also too expensive and their fire resistance is currently not adequate for structural use. Fiber reinforced gypsum board is, conceptually, an attractive candidate for the interior face of a panel. It has impressive cost and fire properties and is a good candidate for the inner face of the panel if its lack of tension strength can be overcome. It may be possible to solve this problem macroscopically with steel reinforcing straps at the rib locations or with fiber reinforcing within the material itself. The material technology, however, is not yet ready and so was not available for use on the proof-of-concept structure.

Structural wood panel materials are common in U.S. light frame construction (section 2.1) and are often used in foam-core panels as well. They are inexpensive and possess a good stiffness to weight ratio. The strongest wood candidates are plywood, and two of its substitute materials; waferboard and oriented strand board (OSB).

Plywood has been the dominant structural panel material for U.S. light frame construction since the mid 1940's. It is used as sheathing on walls, floors and roofs. In 1975, waferboard, and then later, OSB was introduced. Within the past 10 years they have begun to take away a significant portion of plywood's market share in these applications [Montrey, 87]. OSB's advantages over plywood include: not requiring high grade raw material, the ability to make larger sheets, better dimensional stability and lower cost. OSB's major obstacle is that of perception. The original waferboard products, to which OSB appears similar, were low quality and developed a very poor reputation among builders and consumers. The main problems were low strength and poor dimensional stability resulting in thickness swelling at the edges. Although significant variation among producers remains, the resins used to bond OSB and waferboard have been much improved, largely eliminating these problems.

Over the current waferboard material, OSB has advantages of higher strength and slightly lower manufacturing costs. According to Montrey, "there will be a movement among waferboard producers to change to OSB." and "over time, OSB has the potential to become the dominant plywood substitute." [Montrey, 87]. This will be due to lower manufacturing costs, higher performance and minor switchover costs. Montrey forecasts that half the structural panel market in the U.S. would be unveneered (OSB or waferboard) by 2000 and by 2030 it would be 100%. These forecasts, made in 1982, were confirmed by an update in 1987 [Montrey, 87]. Indeed, today waferboard is made by only a few manufacturers. These reasons, in addition to consultations with the sponsors and advisors led the IHCTP to select OSB as the material for the panel faces and ribs.

With the OSB ribbed panel design in place, there are many choices available for the insulation. Structural requirements have been eliminated, leaving insulation value, manufacturing concerns and a few lesser performance requirements remaining. The insulation must be able to provide R-30 within a reasonable panel depth as determined by the OSB structure, and the form of the insulation should compliment rather than hinder the manufacturing process. The interior depth of the panel is likely to be in the 9 to 12 inch range, in intervals corresponding to dimensional lumber depths (9-1/4" (x10) or 11-1/4" (x12)) to retain compatibility with conventional construction (section 3.11). To accommodate venting (section 3.13), the space available for insulation is reduced by one inch. The remaining depth available requires an R-value for the material of 3.3 to 4 per inch to approach an overall value of R-30 for the panel.

Material options include fiberglass, perlite, rock wool and cellulose (table 4.4). Fiberglass, rock wool and cellulose all meet the insulative value requirements at low cost. Cellulose, however, is vulnerable to moisture (table 4.7), causing it to be innapropriate for application in a roof envelope panel. Fiberglass was chosen because it can be formed into batts or blown with a binder enabling it to retain its shape in a panel. This ability is crucial so the insulation can retain its form in the panel through shipping and handling and doesn't settle to the eave of a sloped roof panel.

Table 4.7 : Properties of insulation materials
Source: [Nisson, 85]

Insulation Material	Water absorption	Moisture damage	Fire damage
Cement foam			
Fiberglass Batt Insul.	G	E	G
Loose fiberglass	G	E	G
Rock wool	G	E	E
Cellulose	P	P	F
Perlite	F	G	G

P = poor, F = fair, G = good, E = excellent

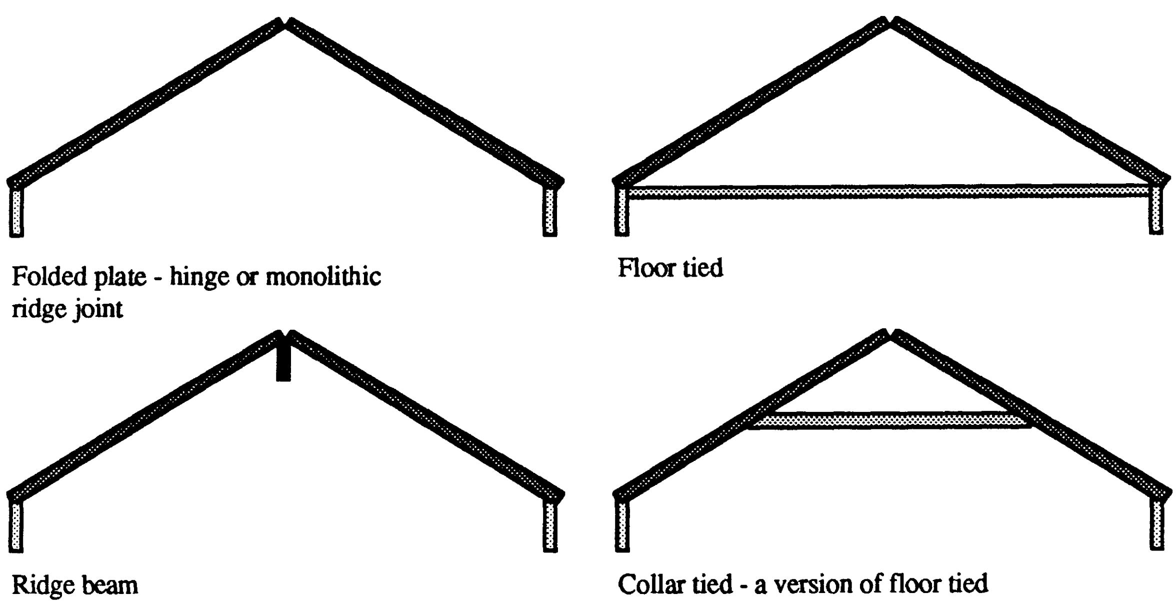

Figure 4.5 : Basic pitched roof structural strategies

4.1.8 Structural options for the pitched roof

There are four ways to hold up a pitched roof: with a rigid (moment resistant) ridge connection, a folded plate, cross tied (or truss), or a ridge beam (see figure 4.5).

Moment resistant ridge: If the ridge line of a gable roof is a moment resistant connection, the roof will span between the two side walls of the house in one span, like a sharply bent beam. The roof panels span twice the distance as in the the other schemes and therefore must be four times as stiff (EI proportional to L^2, where I is the moment of inertia and L is the span). It is very difficult to make a fully moment resistant joint in the field, therefore this option is not generally used except in its variation with flat or shed roofs where there is no ridge line.

Folded plate: A folded plate pitched roof uses the plates (the two sides) of the roof as beams. Each side acts as a deep beam to support the other side along the ridge line. The loads are carried out to the gable end walls where they are resolved in a tension tie. Folded plate action eliminates the need for trusses, ridge beams and collar ties, but requires substantial stiffness overall [Kucirka, 89].

The behavior of folded plates can be separated into two independent actions - "slab" action and "plate" action. The bending strength of the sandwich panel spanning between the eave and ridge line is the "slab" action. The shear stiffness of the entire side of the roof in the plane of the roof is the "plate" action (also called diaphragm action). This "plate" action in one panel provides support for the "slab" action of the opposite panel along the ridge line.

Through "plate" action, the load is carried out to the ends of the plates at the gable end walls where the outward thrust is resolved in a tension tie and the downward loads are carried by the end wall or corner posts.

Theoretically, the folded plate is a simple structure without the expense of a ridge beam, or the expense and space interference of collar ties or trusses. There are many considerations, however, which prevented the folded plate structure from being chosen as the primary structural scheme for the panelized roof system. These considerations include construction difficulties, the non-redundant structure, difficulties with complex roofs, roof openings, future renovations, and higher stresses in the panel to panel joints.

• Construction difficulties: Not until all of the panel-to-panel joints and edge supports are connected will the folded plate develop any rigidity. The roof panels must be suspended in their aligned position so they can be joined. This implies a great deal of temporary construction, which is contrary to the goal of rapid construction and more than likely counteracts any savings from the absence of a ridge beam, collar ties or trusses. The folded plate may be appropriate in the case of a small roof part (a dormer for example) which may be composed of one panel for each side.

• A folded plate structure is non-redundant. That is, if one part of it fails there will be a catastrophic failure of the entire roof. If one of the tension ties in a gable wall fails, if a panel to panel joint should slip, or if a panel should fail in shear or bending, the whole roof could come down.

• The design and analysis of complex roof shapes is very difficult with the folded plate structure. The placement of roof openings (such as skylights, turn gables, dormers, penetrations for services) is critical. Both bending (the "slab" action) and shear (the "plate" action) must be carried around the openings.

• Future renovation of the house may be impeded by the strict structural requirements of the gable end walls and the roof plates themselves. In addition, a lack of understanding of folded plate behavior on the part of a future builder could lead to a dangerous situation.

• The "plate" action of the roof plane imparts a large shear load to the panel-to-panel joints, especially towards the ends of the roof. This load tends to try to make the panels slip by each other in the plane of the roof and the loads are a permanent part of the roof structure. Typically, shear in the roof occurs in response to lateral wind or earthquakes and is therefore temporal. In a folded plate, these loads are much higher than with other methods of roof construction [Kucirka, 89]. Since the panel-to-panel joint is one of the most important joints and one of the most difficult to design (section 6.3.1), this is highly undesirable.

• Above all, the interaction of forces among the panels depend upon each roof geometry. In a manufactured system, this forces standardization of panel depth and joint design at the level of the worst case possible - an expensive proposition.

Cross tied (truss): This is the most common method of holding up wood frame roofs. The rafters from each side of the gable lean on each other, resulting in an outward thrust at the side walls. The outward thrust is resisted by tying the rafters together across the house either with an attic floor or with collar ties. The structure performs as a truss in this configuration. Prefabricated wood roof trusses use this same concept with a more efficient use of materials and labor at the expense of occupying most of the roof cavity space for structural members.

Ridge beam: Using posts and beams, this method of roof support eliminates the transformation of vertical loads into horizontal thrust at the walls. The ridge beam divides the roof structure into two simple spans between eave and ridge. The roof panels span this way in one-way beam action (the "slab" action referred to in folded plate behavior). Diaphragm action in the roof plane is present only to resist horizontal wind and seismic loads. This is similar to the "plate" action described in folded plates, but at lower magnitude, and less frequently.

The major structural advantage of the ridge beam is that for primary load carrying (i.e. not wind and seismic), each panel is structurally independent, not depending on the whole house design. This obviates the need to design and build every panel and joint in the system to meet the requirements of the worst case single house design. The major architectural advantage of the ridge beam is an almost completely unobstructed roof cavity space.

The ridge beam and the cross tied methods were the two strongest candidates for application to the panelized roof. Cross-tying the structure eliminates costly beams and the architectural constraints imposed by the supporting posts. It is the most common structural method used in rafter framing. The advantages of a ridge beam outweigh these benefits when the roof is panelized, however. The construction procedure and sequencing are vastly simplified with a ridge beam. In the tied scheme, panels are not stable until the opposite panel is in place and the tie connection is made. Temporary structures or complex hinged rigging [Kucirka, 89] would be needed to install cross-tied panels. With a ridge beam in place, each panel can be dealt with as structurally independent for purposes of erection and primary load carrying.

Although significant engineering attention must be paid to the design of the ridge beam and its supports, a cross tied scheme could require even more attention as roof complexity increases. Turn gables, hips and asymmetrical roofs create many combinations of complex cross-tying situations that may be difficult to accommodate within a manufactured building system.

Finally, the selection of a ridge beam provides opportunity to provide much more than just structural support as can be seen in the ridge beam design (section 6.3.2).

4.1.9 Manufacturing

There are three generic strategies to transform the raw materials into the components of a specific house:

1. Field alteration. Components would come to the site in a small set of standard sizes. They would then be cut to fit the needs of the specific design being built, much as a sheet of plywood or drywall is done with stick built houses.

2. Catalogue of standard parts. The components would be manufactured in a number of fixed sizes from which a designer would choose to create the specific house. The number of sizes (or catalogue of parts) can be large - in the hundreds at least. This is the way windows, for example, have been traditionally selected for most stick-framed dwellings.

3. Custom manufacture. In this strategy, components are made to order directly from the plans of a specific house. The designer is free to design anything within the physical capabilities of the individual components of the system, which arrive on the site ready to be installed.

A customization strategy that requires field altering each component is contrary to both strategies identified as potential ways of saving money in homebuilding: reduction of construction time and adding value to components. This does not eliminate the possibility, however, that the components may be field-alterable, meaning that, in our case, the panels may be adjusted to accommodate unplanned circumstances. Field altering panels on a regular basis, however, would adversely affect construction time by requiring more site work. It also reduces the opportunity to add value to the component, since edges, connection hardware and finishes would have less potential to be pre-manufactured into the panel.

In setting up ambitious design goals (sections 3.1, 3.2 & 3.3) we put major design constraints on the manufacturing process of the roof system components. These constraints do not leave much room for the possibility of a roof system made up of a catalogue of standard parts. The catalogue of parts would become too large to even keep the drawings for them all on file. Misawa, an open wall panelizer, had 5,000 wall panel types in its system. For roofs of varying slopes and widths, the number is even larger, being estimated at 500,000 to 1,000,000 parts under today's demanding designer market[3]. Even this large number of parts could not meet the strict design flexibility requirements set up for the roof panel system.

Custom manufacture of individual components for each house is feasible, and is one of the the fundamental purposes of 'lean', or flexible, manufacturing as described in section 3.7. The technology for flexible manufacturing is available and widely used. Marvin, a window manufacturer, shifted to a custom manufacturing system and has since seen its share of the market grow dramatically. CAD-CAM interfaces, X-Y cutting tables and computer-controlled inventory-tracking software allow the individual design, cutting, assembly, tracking and shipping of different size and shape components for many customers on the same primary manufacturing line or at an intermediate location such as a wholesaler. It was concluded that this would be the best manufacturing strategy for the panel system.

Figure 4.6 is a hypothetical manufacturing line for the ribbed panels. Capitalization (not including development costs) for this line may range from $200,000 to $1 million, depending on the level of automation. At its most automated, the line may require as few as 4 workers, making scheduling and fluctuating the up and down time of the line a simple matter. In the least automated case, all operations and handling except for the rib assembly operation may be done manually.

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[3]Advisory Board

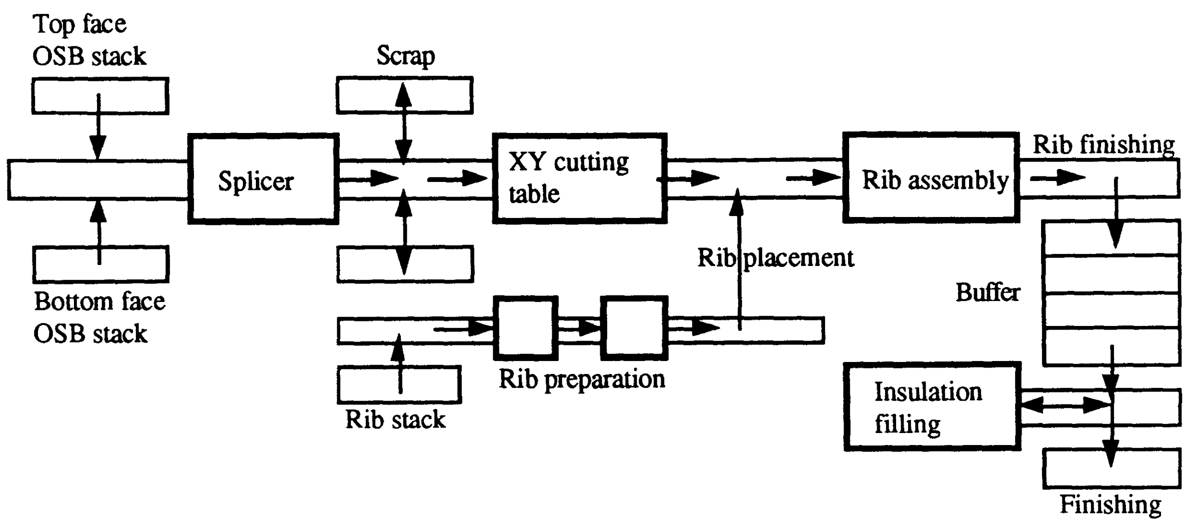

Figure 4.6 : Ribbed panel manufacturing line
Source: [Parent, 91]

4.1.10 Panel width - 4 feet

The roof panel system has, up to this point, been set up as eave to ridge spanning OSB ribbed panels. The question of the width of these elements will now be addressed. Of primary importance in this decision are the weight and dimension constraints outlined in section 3.9. Custom manufacturing, as described in section 4.1.9, means that the length and angle of the panels can be individually specified, but the width is constant. Odd width panels can be fabricated off-line, but the number of these should be kept to a minimum. The design and dimensions of the final product - the house - also influences the optimal width of the panel element.

We have selected a panel width of four feet. There are a number of reasons why we did not opt for a wider unit (specifically an 8 foot width). The reasons fall into the following categories: manufacturing, erection and design.

Manufacturing:

Based on manufacturing and raw material limitations width options boiled down to three. These three were an eight foot width, a four foot width and a smaller width (12" or 16") called a "plank" width. These are the only feasible panel widths for the near term solution. Because OSB is produced in eight foot widths, panel widths not evenly divisible by eight feet would result in much material waste.

The smaller 4 foot wide panel is easier to manufacture and handle in the plant than an 8 foot panel. Costs of manufacturing equipment go up linearly with increased width. This applies to roofing materials for a pre-roofed panel as well[4].

Transport and erection:

A 4 foot wide panel will weigh half as much and have half the surface area of an 8 foot wide panel. The OSB ribbed panel, as designed, weighs approximately 4.5 pounds per square foot (not including roofing). A 4' x 20' panel weighs 360 pounds which is within the 400 pound maneuverability limit and well below the 700 pound crane limit established in section 3.7. An 8' x 20' panel, weighing 720 pounds, is greater than both these limits. Pending tests on the proof-of-concept structure, the maneuverability weight limit may be relaxed if joints align easier than expected. Eight foot wide panels can be tried on the proof-of-concept structure and may prove to be constructible.

Doubling the panel width to 8 feet would halve the number of crane lifts - but in addition to possibly increasing the size of crane needed, it also may increase the care, and therefore time, needed on each lift. Packing the 8 foot panel may be simpler but since the 4

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[4]Private communication with GE Plastics and GAF Corporation.

foot panel is half the 8 foot panel's width, it can be packed just as efficiently, and may provide increased flexibility.

The 8 foot panel would have half the footage of panel-to-panel seam. These joints, however, would have to be easier to align and more durable to facilitate the connection of the larger, heavier panels.

Architectural design:

There is evidence showing that a 4 foot exterior planning module for housing is acceptable. "Components In The Homebuilding Industry"[Deitz, et. al., 60], a report published in 1961, studied 8 custom designed houses and concluded that: "with 48-inch exterior wall components...custom-designed houses can be converted to component construction without undue distortion"[Deitz, et. al., 60]. It is important to note that a larger module was not attempted. In the case of roof panels, the house dimension is restricted in one dimension only (except for hip roofs). The dimension corresponding to the horizontal projection of the length of the roof panel is unrestricted.

Figures 11 in the report (figure 4.7) depicts the cost of manufacturing (labor and materials) as a function of the panel length. The panels grow less expensive per square foot as they become wider. However, the curves tend to flatten out at the 4 foot point. This results in a small cost difference between 4 and 8 foot wide panels.

4.1.11 Connection details

See chapter 5 for an in-depth discussion of the design of the connection details.

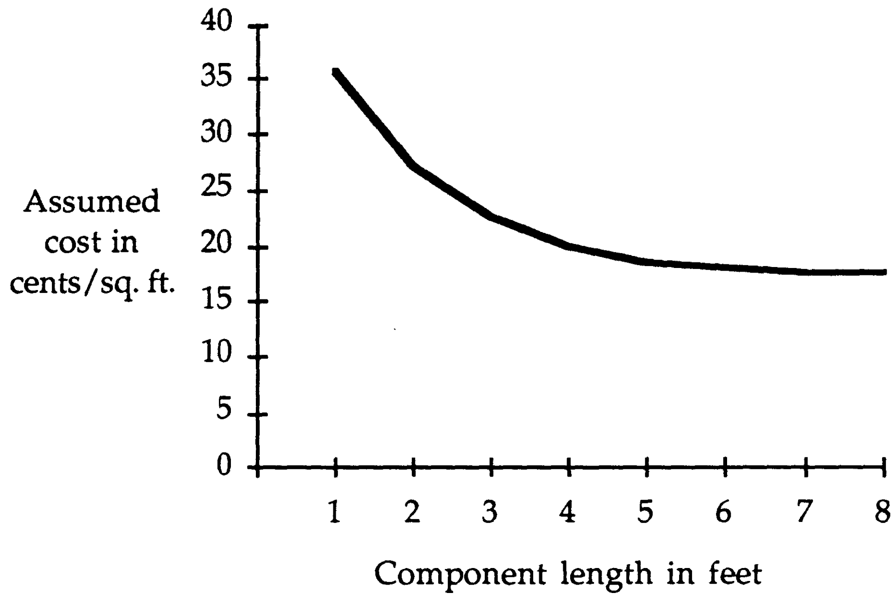

Figure 4.7 : NAHB components study, general cost curve for solid exterior wall panels. Source: [Deitz, et. al., 61]

4.1.12 Finishes

Interior

Since the quality of finish and flexibility of choice of the interior finish material is so important, and since the market is so strongly predisposed towards the traditional painted gypsum wallboard type finish, it was decided not to completely finish the panels in the factory. A base layer would be provided on the panels which could be taped and painted similarly to drywall, or upon which could be applied a finish layer of wood or other material. This material would need to be durable and provide the required fire resistance. At the time of the POC structure, this material had not been determined.

Exterior

There are even more choices available for exterior roofing, which is very important in determining the look of a house. As emphasized in section 3.2, flexibility here is essential. Conventional roofing materials can be applied over the panels. Additionally, a number of innovative roofing ideas are being investigated for the POC structure. These include standing seam metal roofing (appendix, section A.1.2), and 4' wide embossed asphalt rolled roofing.

CHAPTER 5 Joint design

5.1 The Pugh design process

This chapter focuses on level 12 of the decision tree; the design of the panel connections. These joints, of which there are many types (panel-to-panel, ridge, eave, hip, valley, rake, gambrel, wall intersection, etc.) were designed using an inter-disciplinary method based on the Pugh Design Selection Method [Pugh, 81]. The hypothesis behind this method is that finding ideas, or solutions to a problem, are not the problem. Rather, sorting out the ideas to ensure that only the best ones are developed through to completion is the difficult, and critical, part of the design process. The Pugh method addresses this difficulty through methods that encourage sound technical debate and a thorough understanding of all the design concepts. Although it is called a "*selection* method", the Pugh process is a stimulant to creativity. It is intended to find better concepts, not just select from a static set.

In this method, a number of equally developed design concepts are compared to a carefully composed list of design criteria by an interdisciplinary group in an interactive manner. In our case, the group included architects, structural engineers, mechanical engineers, and manufacturing experts. The sessions revolved around a matrix sheet containing the criteria; listed down the left side, and drawings of the concepts across the top. One of the concepts is designated the 'datum' and all others are compared to it based on the criteria, one at a time. In the box corresponding to the intersection of a concept and a criteria a mark is placed. If the concept is judged by the group to be better than the datum, a '+' is inserted. If it is judged worse a '-' is inserted and if the concept performance is judged similar to the datum or if the group can not come to agreement, a '0' is placed in the box. The score is not tallied up at the end, but the the act of having to put down a mark forces thought and debate about the concepts and the design problem.

The idea to use a method like the Pugh process came about from a need to choose between the many joint concepts we had. The design group struggled for a long time for a method, short of building them all, that would objectively evaluate and thereby help select the best of the design concepts. There was a fear that without a good method which yielded results we could be confident in, the group would risk losing potentially valuable ideas and information by eliminating concepts.

Each joint was dealt with in a two week period, containing two interdisciplinary group meetings. The original concepts came from months of idea generation and discussion by many participants in the ICTP. The first meeting began with between five and eight joint concepts. The selection of concepts attempted to cover as broad a range of solution types as possible by including all the joining techniques and strategies available. These would then be mixed and refined to come up with the best combination(s). The first concepts can be seen as raw material, used to build better concepts.

In the week between the two meetings, the results of the first session were examined. The concepts for the second meeting were developed based on these results. The first hybrid designs evolved during this time and the poor concepts and attributes, as determined in the first session, were eliminated. The second meeting began with these refined designs. There were usually fewer concepts, allowing them to be explored more thoroughly. By the end of the second session, the group was beginning to converge on a solution. This solution would then be worked out in terms of dimensions and materials during the ensuing week. Eventually it would be built at full scale. The mock-up would be the final test. It was conceivable that the design would fail this test (this happened with the panel-to-panel joint, section 6.3.1). In that case it was back to step one.

The order in which the joint design process was done was important. The most critical joints - joints which are most common in roofs and would have the maximum effect on the roof system assembly and performance should be designed first. Also, considering the timeframe of this thesis, it was unknown whether there would be time enough to apply the Pugh method to all joint types. The first joint designed was the panel-to-panel joint. It was followed by the ridge, eave, valley and hip respectively. Joint conditions not included in the proof-of-concept roof were not designed.

The Pugh design process was started as a design *selection* method. It soon became a way to *generate new* designs that were clearly superior to the original concepts, thereby allowing the elimination of the older designs. It did this by creating designs that incorporated the advantages of the original concepts while eliminating their disadvantages.

5.1.1 Criteria list

The first step in the Pugh Design Selection Process is to make a list of criteria, or requirements, that the designs must meet. These criteria are not quantified minimum standards, rather they are specific issues to be used as a basis of comparison between two design concepts. The requirements should be generic, i.e. not concept dependent. For example, "redness" is a concept dependent criterion because it assumes all concepts are red. The proper criteria in this case would be "color" because there may exist a valid concept that is blue.

In the interest of time, the list should be of minimum size while still being all-inclusive of the important issues. Redundancies - criteria that are subsets of each other - should be eliminated. The list will ultimately be a summary of all the issues and goals surrounding the design problem. As the list enumerates the goals of the design problem, it becomes the problem statement. The list will be used as a tool to compare all the design concepts and should be developed carefully with the interdisciplinary team. The best way to be sure the list is acceptable (and a good way to develop it in the first place) is to test it by fire - with a few trial runs. This will bring out the redundancies, omissions, and especially the concept dependent criteria.

In the case of the roof panel system, there were multiple design problems (ridge, eave, etc.) sharing many of the same criteria. One criteria list was used, with a few minor alterations depending on the joint at hand. The universality of the criteria list is strong evidence that the list is concept independent.

The first draft of the list had 20 criteria. It was drastically revised during and after the first two design sessions. The list was further revised and expanded from 21 to 39 criteria as a result of consultation with experts in the building systems field[1]. At this point it was also merged into one master list applicable to all joint types. Subsequent design sessions pared the list down to a manageable size of 32 criteria. The list was not finalized until the 6th session and it is still subject to alteration with each new use.

Prominently absent from the criteria list are any structural requirements. Structural performance was considered a binary requirement, i.e. if a concept was not structurally satisfactory then it would not be considered, and overcapacity was not considered a significant advantage.

Joint design criteria and definitions:

Installed Performance

Weather seal (water/wind).

Infiltration seal (air/vapor): Prevent condensation and associated problems

Thermal bridging: Avoid short circuiting of insulated panels.

Fire performance: Meet fire code.

Sound transmission: Outside to inside and vibrations within the structure.

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[1] Advisory Board

Aesthetics: Aesthetics and marketability

Durability of seal: Performance at 10 years old compared to performance when new, assuming ordinary use. Also possible effects on interior finish such as staining, etc.

Durability of structure: Performance at 40 years old compared to performance when new, assuming ordinary use.

Additional features: Space for conduits, etc.

Constructibility

Ease of alignment: Number of axes of alignment needed and tolerance for each axis.

Flexibility of alignment (angle of approach): Number of directions from which the panel can be aligned, for purposes of countering possible obstructions; also flexibility of sequence of installation, i.e. panel A then panel B or vice versa.

Does not require high site tolerances: Dependency of panel system on precise dimensions of building frame.

Special skills or training required (skill level): Slope of the learning curve for workers learning the system; hours of instruction needed for training.

Assembly steps (time): Speed of assembly with an experienced crew

Loose parts: Amount of material a worker must carry up onto the roof.

Ease of trimming & finishing & roofing.

Pre-roofed potential: Implications the joint design may have on the potential to apply the roofing material to the panel in the factory, e.g. fasteners should not pass through the weather membrane.

Robustness: Installation climate independent, e.g. cold weather is bad for adhesives and concrete. Also, adjustability during assembly (second chance), e.g. contact cement is bad, displacement of caulking during adjustment is bad.

Interface with other joints: Condition at joint intersections, e.g.: ridge and turn gable ridge, panel to panel and eave.

Succeptability to damage: Fragility

Field modification ability: Ability to correct a manufacturing or field dimension error and the ability to repair the panel system and make it work in the field, if it is damaged.

Special tools and equipment needed: e.g. hand tools, router, large diameter saw, crane attachments, etc.

Cost & Manufacturing

Universality of joint: Possibility to use similar concept for other joints, thereby sharing manufacturing equipment and worker skills. Also applicability to all roof designs - slopes & spans.

Does not require high manufacturing tolerances.

Dimension of panel (for: manuf., transport, design): Compatible with standard material and manufacturing equipment sizes, packs well for transportation.

Ease of integration into panel edge: Degree of alteration of the panel necessary to integrate joint.

Robustness of manufacturing process: Dependence of process on environmental factors; succeptability of foul-ups.

Capital cost: Cost of plant, not including cost of capitalization of plants supplying materials and components.

Parts & materials cost: Cost of all purchased materials and components.

Number of parts in assembly

Assembly labor: Man hours required in factory.

Assembly speed: Time between order and shipping.

5.2 Tolerances

Before progressing to the example of the eave design process, it is necessary to talk a bit about the tolerances of the system. This is a subject affecting all joint and system design decisions and must be presented here so that the reader will understand the discussions relating to this topic in the eave example.

During the design sessions, much attention was devoted to the issue of construction tolerances and how they may affect the roof panel system and the joints in particular. The concern was that the tight manufacturing tolerances of the prefabricated roof panels would not mesh with the looser field construction tolerances of the foundation and/or walls, resulting in a poor fit between the two systems. This problem could be compounded if the roof panels were not field alterable and by the fact that large panels tend to collect larger errors over longer distances. Concerns over tolerances heavily influenced many of the joint designs.

The hip and ridge joints are most sensitive to dimensional errors in the building frame. At the hip, three prefabricated angled surfaces must come together and rest on a perfectly square building end. Since the building will usually not be perfectly square, discrepancies between the panel hip angle and the building hip angle will inevitably arise. Two tactics to combat this problem are to allow tolerance in the hip joint and to adjust the placement of the ridge beam. The ridge beam can be situated such that it splits the error between the two hip lines where it is then accommodated, half in each side, in joint tolerance.

The ridge tolerance is often problematic in foam-core panel construction. Sometimes the roof panels must be lowered to the ground and trimmed to fit after an unsuccessful setting attempt. This is not surprising since to get a flush fit (which is what the detail calls for in most foam-core panel construction), not only must the panel be the proper length, but the eave walls must be the correct distance apart and the ridge beam must be precisely in the correct position.

An important feature of the panel system will be to create a positive seat for the panel during assembly[2]. The alternatives to do this are to hold the panel in place at the eave, the ridge, or both. It is advantageous to have the roof panel positively rest (caught at a specific point) at only one end, and "slide by" at the other support. This is because of the tolerance issues associated with field built walls as described above and which was also observed in the mock-up of a cam-joint panel in the lab. Here, the panels were registered at both ends and the cams did not line up well (section 6.3.1). Letting the panel slide by one support requires that there is lateral bracing of the support (usually the side wall), which is standard construction practice.

It was decided that holding the panel at the top (ridge) is better because the outside walls are the element most likely to be positioned incorrectly. Also, the crucial tolerance at the ridge will be met automatically if the panel location is registered at that point. The critical dimensions become those between the panel hook and its beveled end and that between the hooks on each side of the ridge beam. These two dimensions are relatively small and both parts involved are factory built.

Another joint affected by tolerance problems in foam-core panel construction is the spline panel-to-panel joint. If the splines do not fit tightly into the panel, and this is not taken into account in the overall panel dimensions, errors can accumulate along the run of a wall or roof. It is common to add 1/8 to 1/4 inch per joint if the splines do not fit tightly[3]. This problem is often caused by thickness variation of the splines or spline cavities.

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[2]ibid
[3]ibid.

Concerns about the tolerance issue are addresses in the tapered spline design of the roof system panel-to-panel joint (section 6.3.1), the ridge hook design (section 6.3.2) and the 'slide-by' nature of the eave joint design (section 6.2.4).

5.3 Example of a Pugh session - The eave

This section describes the process as it was used with one joint - the eave - as an example of the application of the design selection process. For each of the 2 design sessions, assumptions about other aspects of the system (other levels of the decision tree and previously designed joints) are noted. These assumptions were necessary in order to evaluate the joint design at hand.

Each design concept is given a name for reference. The conclusions made about each concept during the meeting are noted, along with more general issues about the joint design problem. The matrix sheet from the first eave design session is reproduced in figure C.6 in appendix C.

5.3.1 The eave joint

The eave joint is where the roof slopes down to meet the wall of the house. It runs continuously along the top of the walls at the sides and the hip ends of the house. The roof comes down closest to the ground at the eave and therefore is closest to peoples' attention, both on the interior and the exterior. Trim details are very important at this high visibility location. Outside, this edge is usually finished with a fascia board and other trim, sometimes quite elaborately. The eave detail often includes vents in the soffit and gutters.

In rafter framing, the structural connection of the rafters to the wall top plate requires notching the rafter ends with a 'birdsmouth cut' (figure 5.1). This is one of the more complex details in stick framing.

The structural requirements of the eave connection in the panel system are threefold. First, it must vertically support the roof panel end, transferring the load down into the wall where it is eventually resolved at the foundation. Second, the eave connection must hold the roof down to the wall to prevent the wind from lifting it off. Thirdly, the eave connection must prevent the panel from sliding horizontally along the length of the eave. This shear resistance is necessary for the roof plane to develop the diaphragm action necessary to resisting racking.

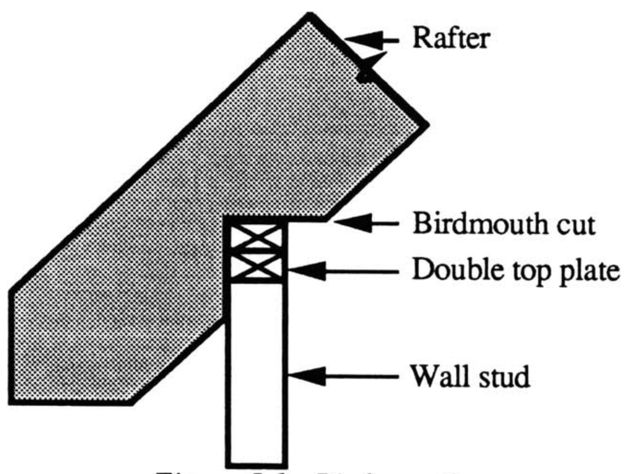


Figure 5.1 : Birdsmouth cut

5.3.2 Eave Pugh session #1

Assumptions: A ribbed panel made of OSB. Walls would be braced during construction as is standard practice in conventional construction. There is a ridge beam, similar to the one developed during the ridge session with respect to its impact on the eave connection (i.e. panel registered at top with hook - see 6.3.2).

Joints: The six concepts for this session are known as: 'Spike', 'Birdsmouth', 'Hinge', 'Frame', 'Ledger' and 'Flat-Bottom' (figure 5.2). They were all conceived of prior to the ridge joint design sessions.

Spike: This connection, which is similar to the eave detail used in existing panelized construction, was used as the datum. It is the only design of the six which has the slide-by attribute. A disadvantage that goes with this attribute is that there is no clue to aid in lining up the wall with the proper point on the roof panels. The wall will have to be plumbed and measurements taken to determine the exact vertical location of the screws. For this reason, it was suggested that it would be advantageous to fasten the panel from the underside where all the relevant parts would be visible. Eliminating the screw through the roof exterior face also facilitates the design of a pre-roofed panel.

Birdsmouth: The name of this design comes from the 'birdsmouth cut' (figure 5.1). This notch is similar to the notch cut in the panel in this design. This joint has good sealing and thermal attributes due to the longer path from outside to inside. A long screw horizontally driven through the top plate into the panel (figure 5.3b) was deemed to be better in resisting uplift, for assembly ease, and for finishing than an angled metal plate with screws as originally designed. Problems with Birdsmouth include the field tolerance issue (section 5.2), interference with the panel-to-panel joint where the two joints intersect, and probable manufacturing difficulty.

Hinge: This joint did poorly in most performance criteria except structure. An interesting feature, shared with Frame, is that the panel end can be trimmed before attachment of the hinge element to overcome the field tolerance issue. Aesthetic interference at the eave detail is a major problem and although Hinge is pitch universal,

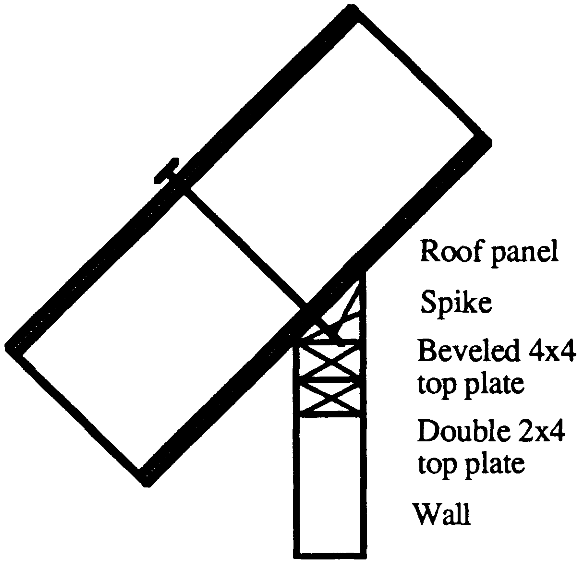


Figure 5.2a : 'Spike'

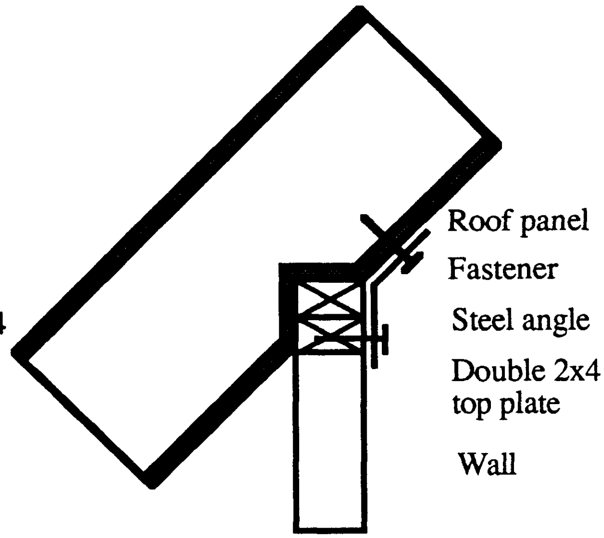


Figure 5.2b : 'Birdsmouth'

assembly is still difficult because the panel must be lowered nearly directly from above. This is difficult with the existing ridge beam design which ideally is assembled by sliding the panel down into position along the slope of the roof.

Frame: The Frame concept was designed with two goals in mind: to build the connection solely with conventional tools and materials; and to provide an easily trimmable and finishable base for a box soffit. It succeeds in these two goals but many problems persist. The many parts were deemed difficult and time consuming to assemble. It is unclear how the panel will be fastened down. The discontinuous supports make sealing, insulating, and fireproofing, difficult without a lot of field work on the soffit. Leaving the connections to become field-built assemblies runs contrary to the whole purpose of a prefabricated component system.

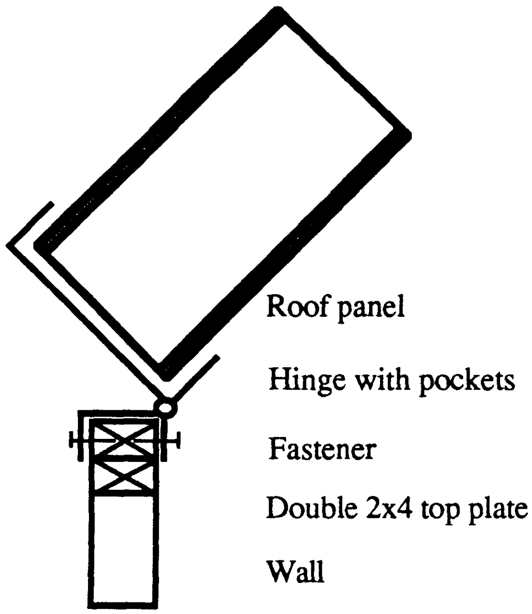


Figure 5.2c : 'Hinge'

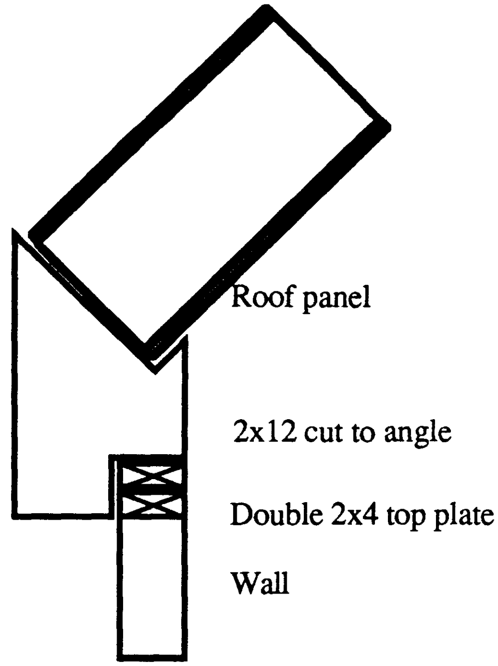


Figure 5.2d : 'Frame'

Ledger: This connection, taken independently, is the easiest to align and provides good sealing opportunities, but the projecting ledger is succeptable to damage, and interferes with packing for transport and with interior finish. The finish problem can be solved if the ledger is triangular shaped to mate with the triangular top plate. The other two problems may be solved with field application of the ledger. Field application may also solve the field tolerance issue by adjusting placement of the ledger based on the location of the wall.

Flat-Bottom: No advantages were seen for this one. Problems are evident with the fold down metal straps. Bending the strap to a precise angle and fold line is difficult. If a pre-scored strap is used, the field tolerances must, once again, be very precise. Uplift will cause the metal strap to flex and pull away from its glue bond with the panel. Only a heavy snow load would cause it to bend back to its original position.

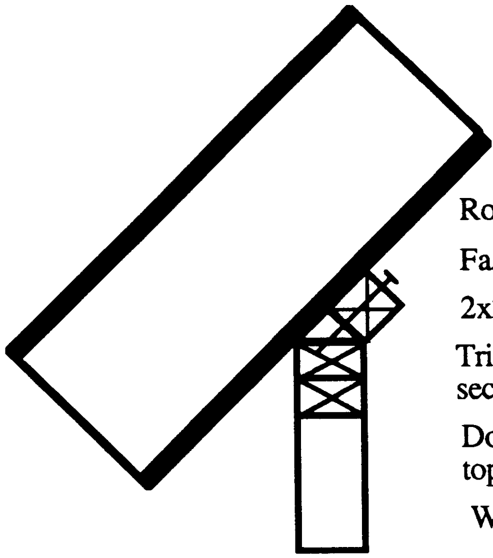


Figure 5.2e : 'Ledger'

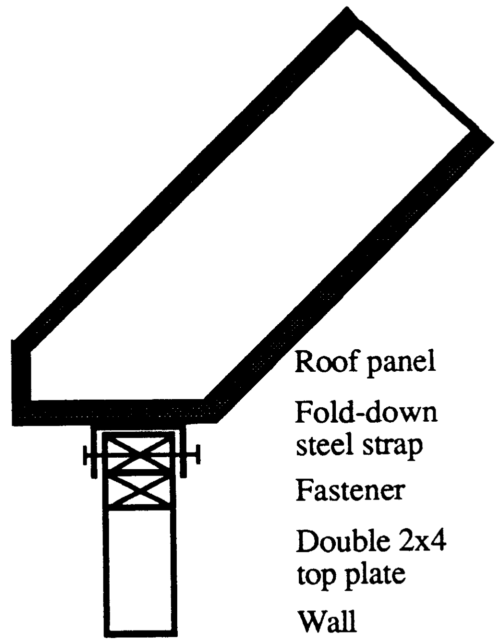


Figure 5.2f : 'Flat-bottom'

5.3.3 Eave Pugh session #2

Joints: Only three joint designs carried through to the second session. These three are 'Screw', derived from 'Spike', 'Birdsmouth', and 'Free-triangle', derived from 'Ledger'. The 'Hinge', 'Frame' and 'Flat-top' designs were eliminated.

Screw: This is a modification of spike and was used as the datum. Instead of a long screw driven down through the panel to provide resistance against uplift, a screw is driven from underneath up through the beveled top plate and into the underside of the panel. A plate will be needed inside the panel to reinforce the bottom face and to hold the screw. While this is undesirable because it adds another manufacturing step, it is nevertheless fairly simple to include.

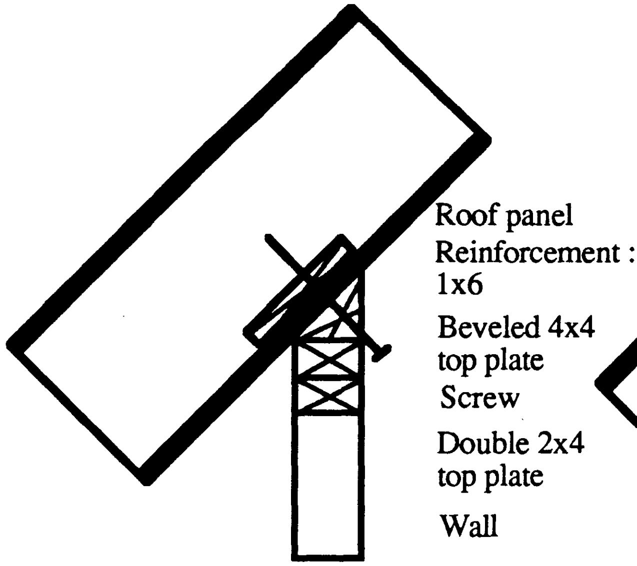


Figure 5.3a : 'Screw'

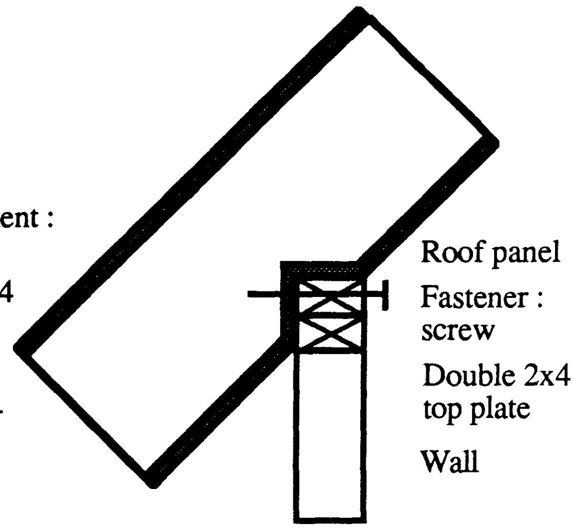


Figure 5.3b : 'Birdsmouth'

Birdsmouth: The new version of this design uses the modification developed during the first session, replacing the angled metal tie down strap with a horizontal screw through the top plate. The field tolerance issue (section 5.2) was not solved by this redesign. Birdsmouth fared poorly in construction and manufacturing criteria while having a few minor performance advantages over the datum (see matrix, figure A.6).

Free-triangle: This uses a beveled top plate similar to Screw. However, this plate is attached to the panel in the field after measurements have been taken. Free-triangle is derived from Ledger of session one, with the ledger becoming a beveled top plate which is field attached to solve the tolerance issue (section 5.2). After the beveled plate has been fastened, it is placed on the wall top and held down with vertical metal straps. Fastening the beveled piece to the panel may require the insertion of a plate in the panel as in the Screw concept.

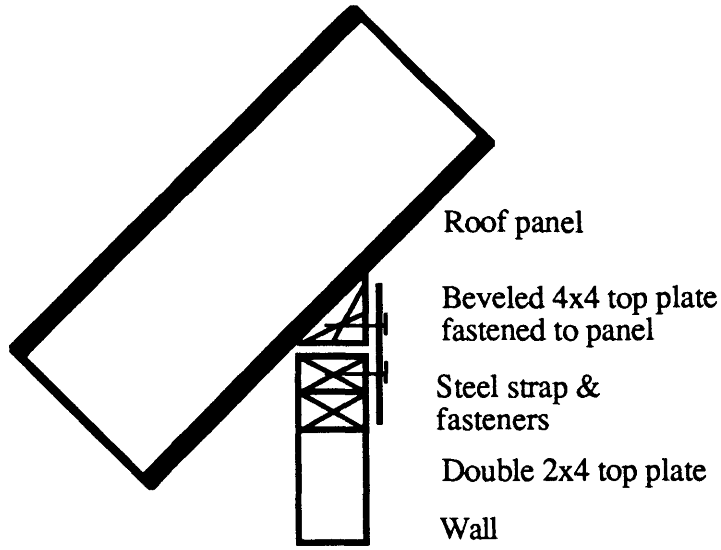


Figure 5.3c : 'Free-triangle'

Conclusion: The Screw and Free-triangle designs have moved closer together until they can almost merge into one. If we assume that the beveled top plate has the same fastening requirements in both cases, the builder has the option to place it on the wall or on the panel first. This builds construction flexibility into the system to suit the unique situation of a particular builder. For example; for hips, bottom registration of the panels becomes an option.

5.3.4 The eave design

The final eave joint design (figure 5.4) is most similar to Screw. It has three parts; one of which is built into the panel, another which is first installed separately on top of the wall, and a third fastening element that makes the connection complete.

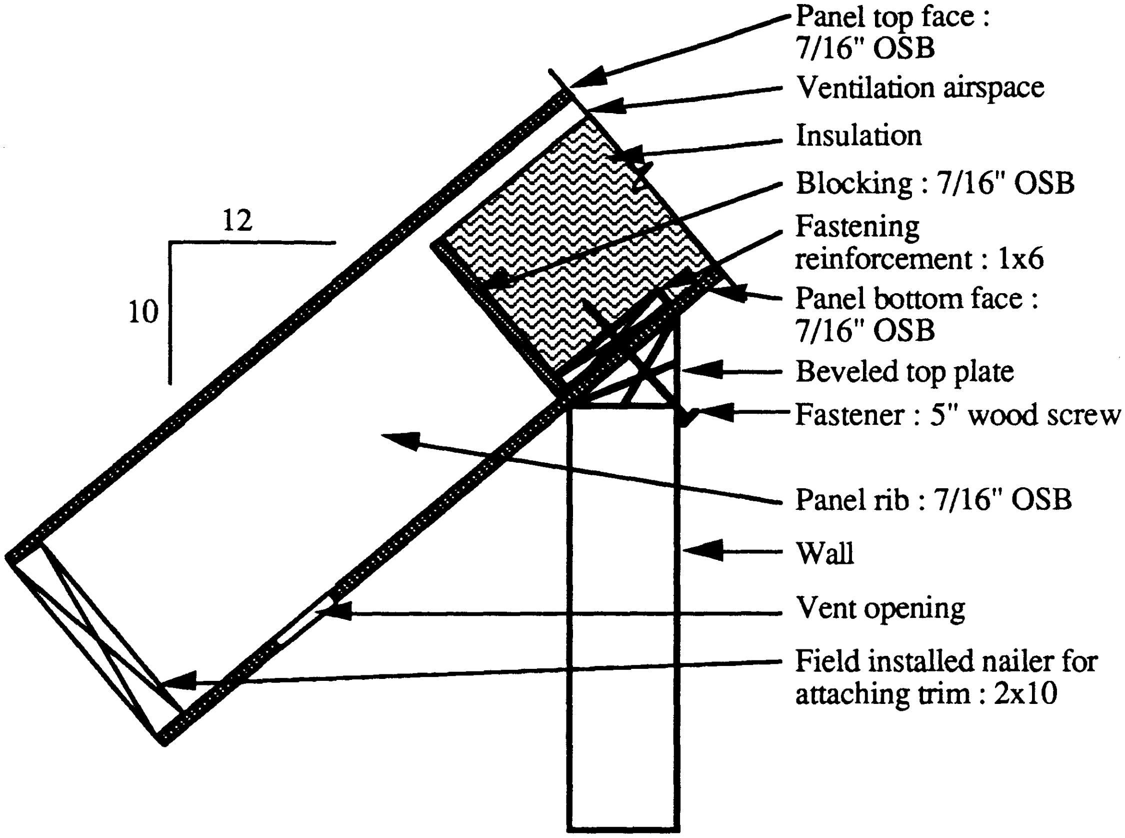


Figure 5.4 : Eave detail; section

The 1 x 6 reinforcement piece is a slight modification to panel production, but it is relatively simple and consistent with modifications at other joint edges. The beveled top plate is also simple to manufacture and install. The fasteners are limited in number, inexpensive, easy to access during installation and consistent with other joints in the system. Overall, consistency among joints is important and the eave retains this attribute, particularly with respect to its opposite - the ridge connection.

CHAPTER 6 The roof panel system

6.1 The proof-of-concept structure

A proof-of-concept structure is being built in East Acton, Mass. on the grounds of Acorn Structures. It utilizes the OSB ribbed panel roof system designed at MIT. This chapter presents the roof panel system design as built on this structure. The intention behind building the proof-of-concept structure is to test and demonstrate the roof panel system in a number of ways. Evaluated will be;

- Site erection of the panels,
- Site assembly and fastening of the connection system,
- Panel structure and material performance,
- Joint weatherability and structural longevity,

The proof-of-concept structure incorporates a gable, turn gable and hip. Figures 6.1 and 6.2a, b & c show the plan and elevations.

6.2 The panel[1]

Both the panel faces and the ribs utilize 7/16" OSB. This thickness OSB is the most common and therefore the least expensive per board foot. There are four ribs per panel resulting in a rib spacing of 14 13/16" on center (figure 6.4). This spacing is close enough for the 7/16" OSB to resist local inter-rib deflections (7/16" OSB is rated for 16" o.c. joist or rafter spacing). Thicker OSB (5/8") was considered, and would have enabled

[1]A more detailed structural analysis of the roof panel and ridge beam is contained in [Morse-Fortier, 91]

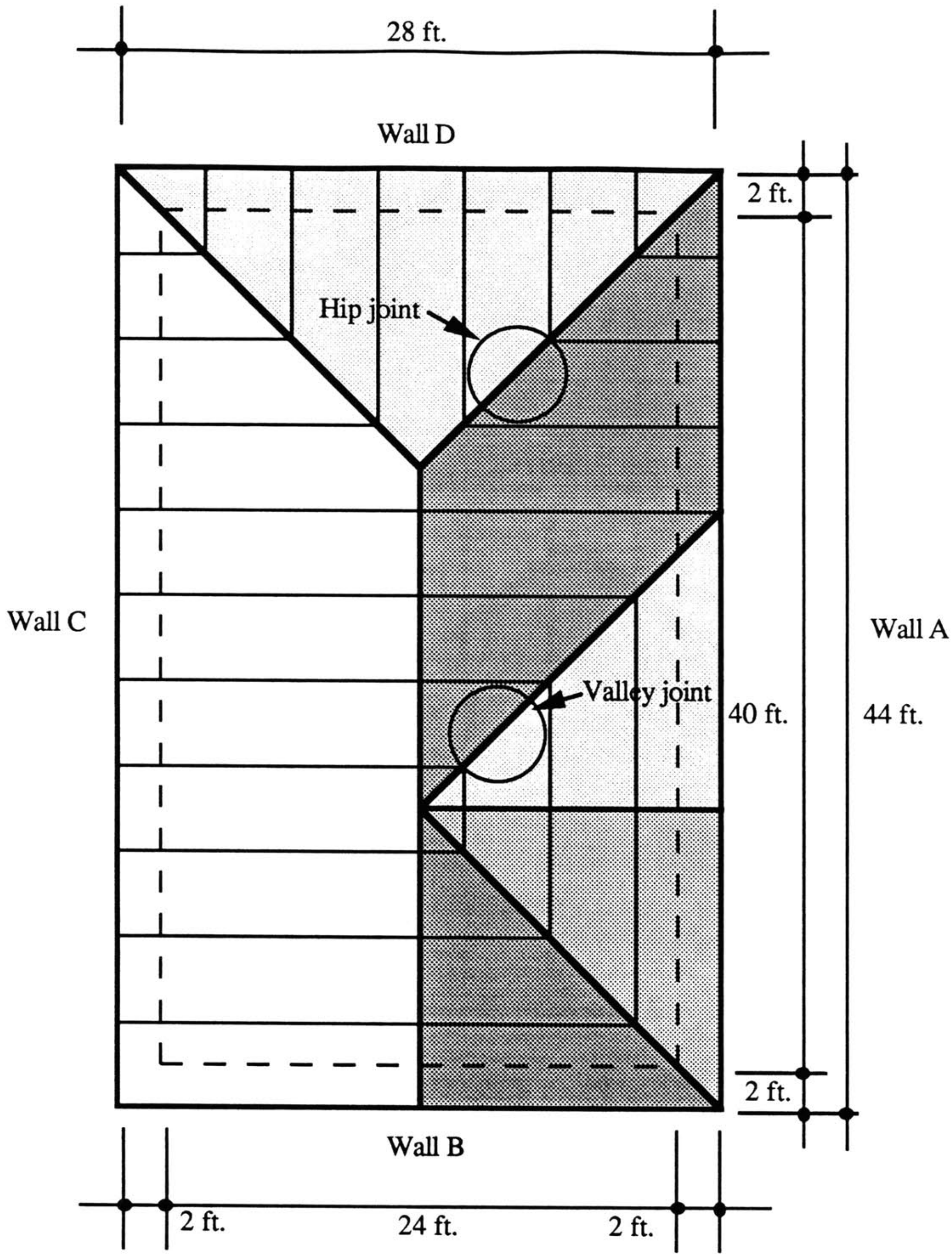
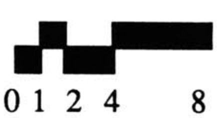


Figure 6.1 : POC plan



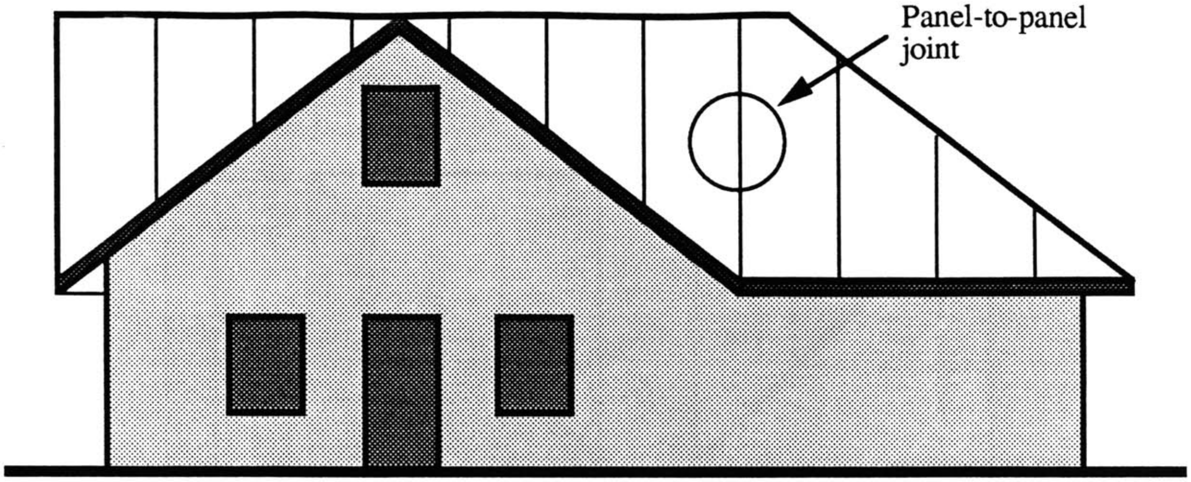


Figure 6.2a : Elevation of wall A

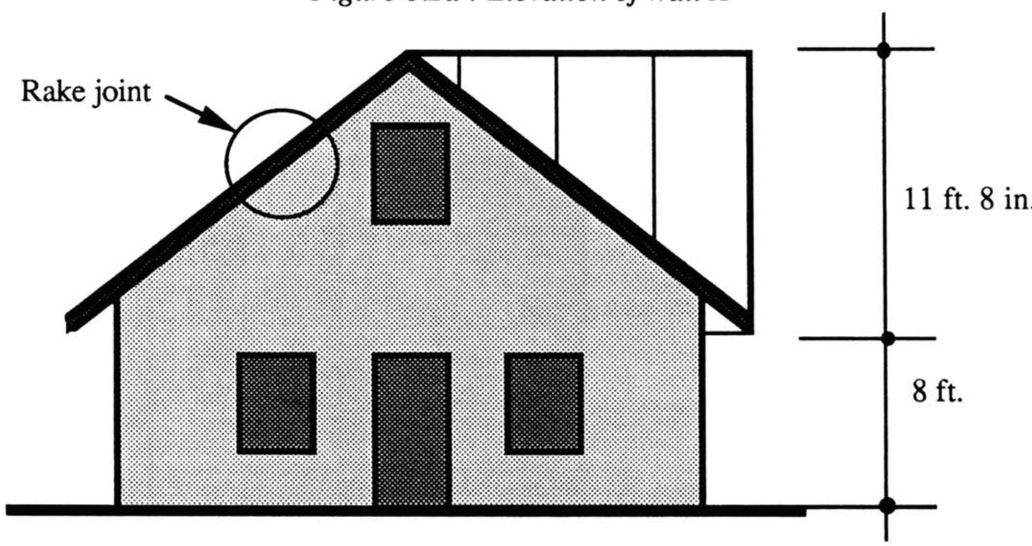


Figure 6.2b : Elevation of wall B

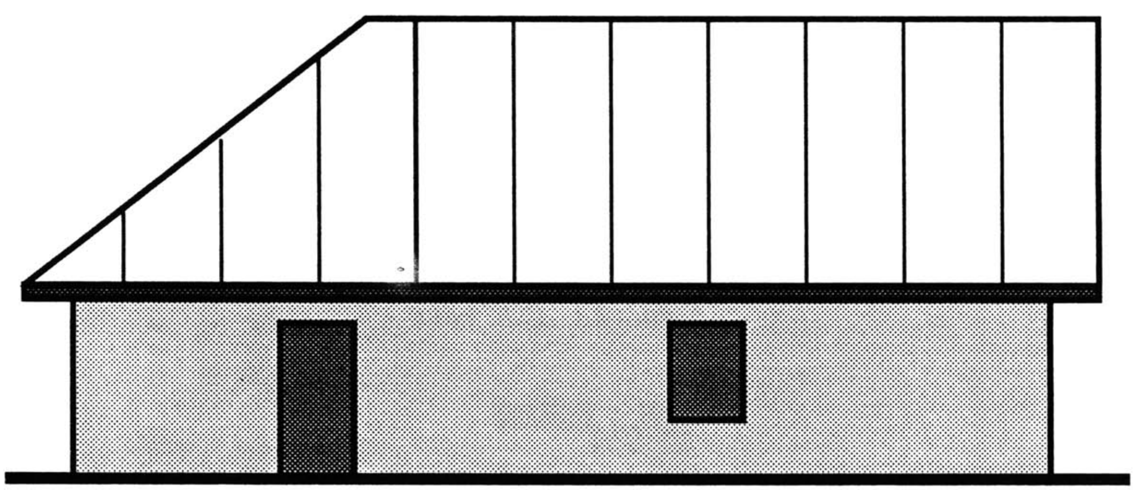


Figure 6.2c : Elevation of wall C

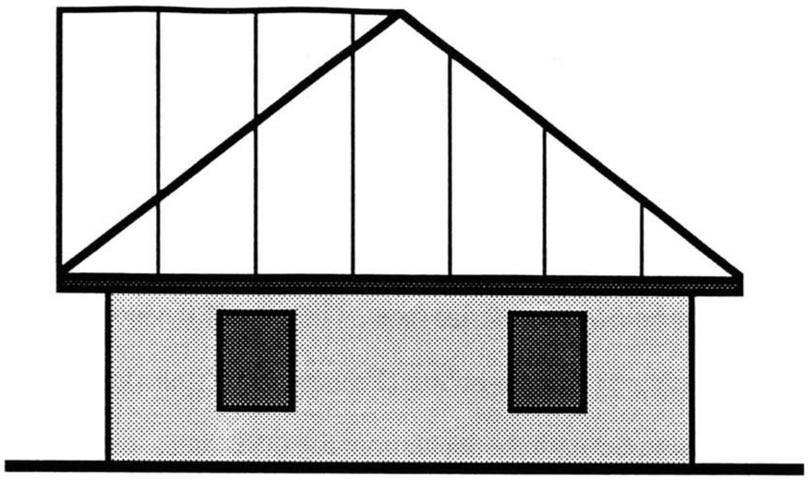


Figure 6.2d : Elevation of wall D

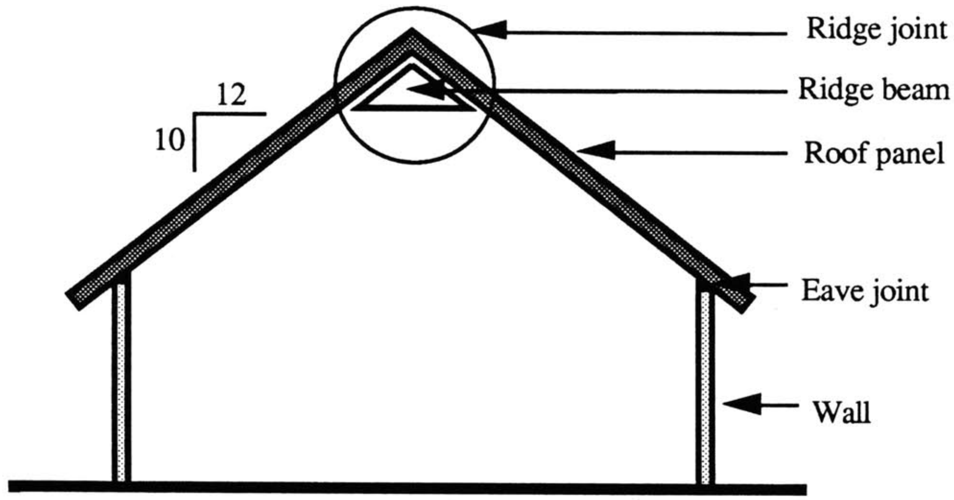


Figure 6.3a : Cross section of POC structure

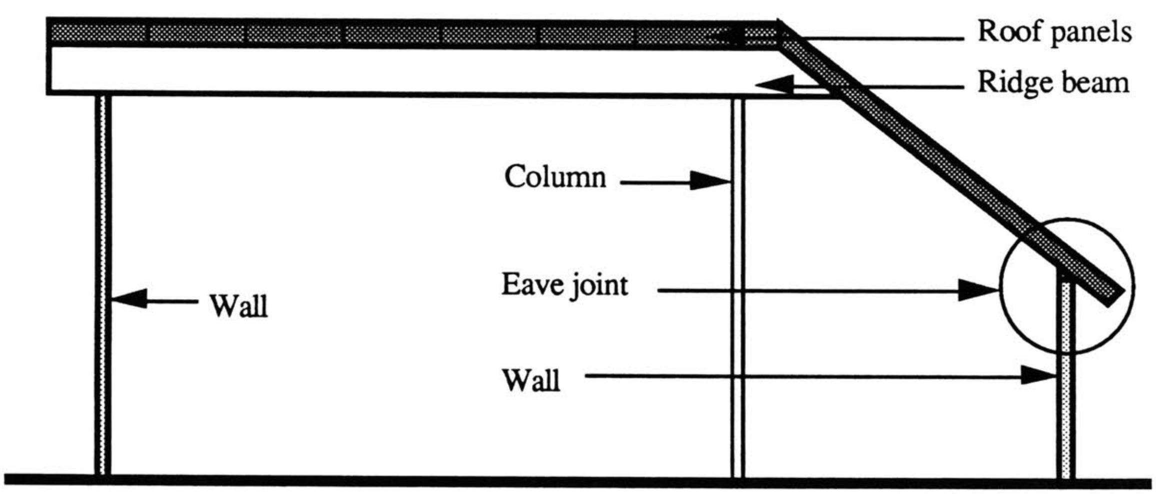


Figure 6.3b : Longitudinal section of POC structure

the use of only three ribs per panel, however the overall panel would have been heavier by 33% and more expensive in material.

The panel is 10.125" thick overall with a 9.25" interior depth, which is compatible with 2 x 10 framing. 8.25" of fiberglass insulation, placed within the panel, leaves 1" venting space remaining below the exterior face. The overall R-value of the panel has been calculated at approximately 31 ft^2 - °F-hr/Btu [Peavey, 91]. 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 plus two dimensional fin effects of the rib (which turned out to be negligible). In the analysis, interior and exterior air temperatures were set at 70° and 0° F respectively, and the airspeed in the venting space was assumed to be negligible. The R-value of the panel was also 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 [Peavey, 91].

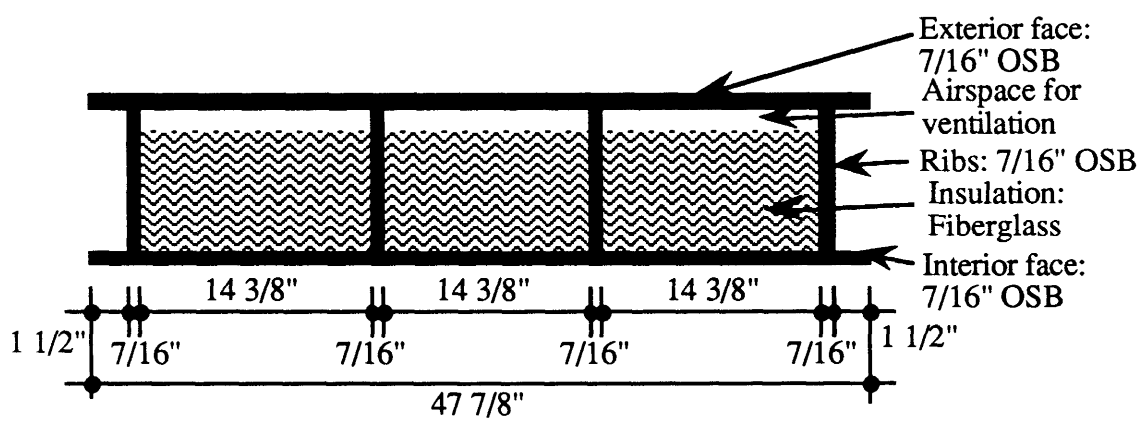


Figure 6.4 : Panel cross section

Special provisions had to be made to provide ventilation for the proof-of-concept structure roof surface because the roof incorporates hips and valleys. Panels on the hip end do not terminate at a ridge vent and those at a valley do not possess eave vents. In conventional construction, hips are not usually built as cathedral ceilings and so there is no need to vent the hip roof surface (because the insulation rests on the attic ceiling, and not in the roof plane). This is not the case with insulated panel construction. In this case there are three choices. One is to vent the panels directly at the hip line analogously to the ridge (with a continuous ridge vent). A second choice is to carry the vented air up the hip line through a channel to the ridge where it escapes through the ridge vent. The third is to notch, or scallop, the tops of the ribs to allow continuous two-way ventilation of the roof. This is occasionally done to rafters in conventionally framed roofs if two-way ventilation is desired. The latter strategy was selected for our design because it allowed the hip joint to remain simple and provided two-way ventilation for the whole roof - a desirable attribute, as described in section 3.13. The design calls for semi-circular holes, 4" in diameter, to be cut out of the rib tops 12" on center (figure 6.5).

The size and spacing of these openings affects both the rate of airflow possible through the roof and the transfer of shear forces from the rib to the face. An analysis of the effects on the airflow rate can be found in appendix E.

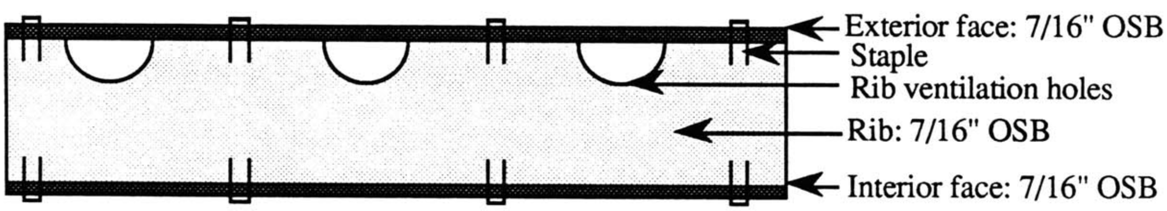


Figure 6.5: Rib notching for 2-way ventilation, panel longitudinal section

As mentioned above, the holes cut in the top of the ribs, for ventilation purposes, affect the structural performance of the panel. The neutral axis of the panel section (figure 6.6) shifts down by .233" or 5% when this material is removed. Under constant bending moment this will cause the induced compression in the top flange (or face) to be higher than the induced tension in the bottom flange (or face) by 10%. This is an advantage, since OSB has demonstrated greater strength in compression than in tension. In a similar product, the published design strength in tension is 725 psi, and in compression, 850 psi, yielding a ratio of .85[2]. Including the ventilation holes not only accommodates the important cross flow of air, it changes the section's structural properties to take advantage of the mechanical properties of OSB.

As designed, the resulting EI of the ribbed panel is $(.7 \times 10^6) \times (1044) = 731 \times 10^6$ in.^{2} lb. As an example of panel stiffness, we consider a roof panel simply spanning from eave to ridge at a 10/12 slope, and subject to a 40 psf (plan shape) live load. The maximum span is governed by deflection, and for an allowable deflection of L/240, L becomes:

$$\delta = \frac{5\omega L^4}{384\,EI} + \frac{3\omega L^2}{20AG} \leq \frac{L}{240}$$

$$\frac{1}{240} = \frac{(5)(94.4)L^3(12)^2}{(384)(731 \times 10^6)} + \frac{3(94.4)L}{(20)(1.40 \times 10^6)}$$

Solving for L yields 25.25 feet. This is the maximum span measured along the length of the panel at a 10/12 slope. The resulting horizontal projection is 19'-5".

Taking into account wall thickness and the fact that the ridge beam supports the panel at approximately 8 inches from the panel's end, it is possible to build a 40 foot wide house with these panels.

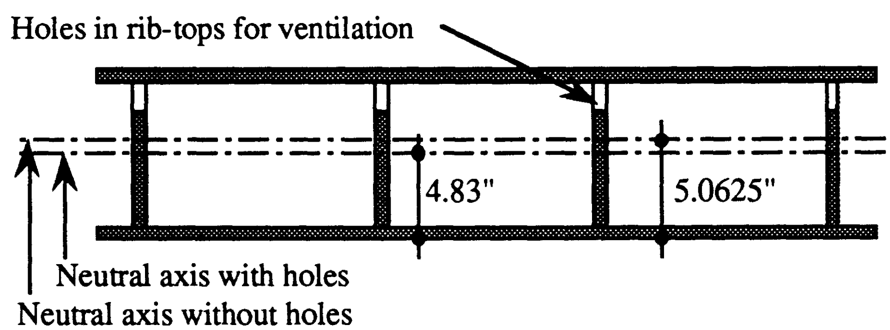


Figure 6.6 : Shifting of panel neutral axis due to rib holes

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[2]From Weyerhauser Struct-One product literature

A major manufacturing issue with the ribbed panel is the interface between the rib and the face. The maximum shear load on this joint for the maximum spanning panel (19'-5" horizontal projection) is 37 pounds per inch of joint in lengthwise shear for a continuous connection (as on the bottom face). For the top face, where, the ventilation holes disrupt continuity, only two thirds of the rib edge is connected to the face and this value increases to 56 pounds per linear inch of joint. This requirement can be achieved best by using a chemical connection. The panels for the POC structure use a chemical bond for the permanent structural connection and a mechanical fastener to aid in glue surface contact and to facilitate the moving of the panels before the glue has set. The glue used is phenol-resourcinol-formaldehyde, which is similar to the resin used in the manufacture of OSB. Staples, inserted with a pneumatic stapler through the face into the rib edges, are used for the mechanical connection (figure 6.5). In tests to failure, the glue bond (without staples) held 500 pounds of shear per inch of joint. The connection failed in most cases by shearing away the top layer of OSB flakes from the interior of the panel face.

Other rib-face connection schemes were experimented with. One of these was a 2-inch wide strip of fiberglass mesh (figure 6.7b), added to the panel face in order to engage more of the OSB flakes on the surface. Another included of small triangular wood sections at the base of the rib (figure 6.7c). The wood sections increase the glue-bond surface area of the joint on both face and rib. A third scheme was to rout a groove in the panel face and insert the rib edge into it (figure 6.7d). Routing is another way to increase the bond surface area, but has negative implications for the manufacture of the panels. In addition to adding a step to the manufacturing process, routing will affect panel assembly. It may aid in alignment of the rib along the panel face, but if the rib did not slip easily into the groove, it could hinder this step. As was seen in the lab, it is very difficult to force the rib into a groove in the center of a 9 foot panel whose opposite face has already been attached. Larger panels would be even more difficult. A 'V'-shaped groove may help solve the alignment problem, but would not significantly increase the bond surface area, would require beveling of all the rib edges as well, and would weaken the face sheet.

All of these connection ideas were pursued to the level of small scale shear testing and some manufacturing tests. They performed better than the butt joint in the shear tests but were clearly unnecessary to meet the relatively modest structural requirements of the system. In short this issue does not govern the panel design.

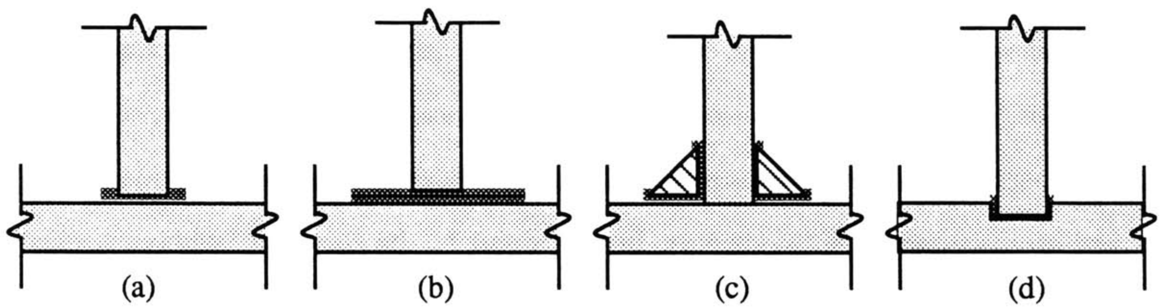

Figure 6.7 : Alternative rib-face connections: (a) butt; (b) fiberglass mesh; (c) triangular wood sections; (d) routed

6.3 Joints

The proof-of-concept structure incorporates a gable, turn gable and hip to exhibit the architectural design requirements outlined in section 3.1. The connection details necessary to form this roof include the eave, ridge, valley, hip, rake and panel-to-panel joints. These joints were designed using the Pugh design selection process described in chapter 5 and are described in the following pages.

6.3.1 The panel-to-panel joint

The panel-to-panel joint is the joint between two panels that are adjacent to one another in the same plane of the roof. With the eave-to-ridge-spanning, 4-foot-wide panel system, the panel-to-panel joint runs along the entire length of the panel.

The panel-to-panel joint must fulfill three structural requirements (figure 6.6). It must resist in-plane shear for the roof plane to perform as a diaphragm. This requirement is imposed mainly by wind and seismic loading and its magnitude depends greatly on the design of the individual house. In the roof panel system, this requirement is somewhat diminished by the high lateral stiffness of the ridge beam design (section 6.3.2). The joint must also resist out-of-plane shear to prevent differential deflection of adjacent panels. Differential deflection may be caused by differing spans of adjacent panels, or by asymmetrical loading due to a person walking on the roof or snow melting unevenly. Differential deflection of adjacent panels may cause unsightly roof seam exposure and tearing of the roof membrane. The final structural consideration of the panel-to-panel joint is tension and compression across the joint. These stresses are induced mainly by constraining the thermal and hygroscopic expansion and contraction of the panel materials. Allowing movement at the panel-to-panel joints will prevent deformation from collecting at the ends of the house where the membrane might tear. If the movement is allowed at the smaller (4 foot) intervals, the roof membrane will be better able to flex and accommodate it.

The panel-to-panel joint is the most crucial joint of the system and the toughest design problem. The solutions for it were the least satisfactory of all our design solutions and, in the end, departed least from existing practice. Listed below are the reasons that the panel-to-panel joint is so important and difficult:

- It is the most common joint with the greatest amount of linear feet.
- It is the joint that represents the system. All others are special conditions that have to do with the geometry of a pitched or gable roof.

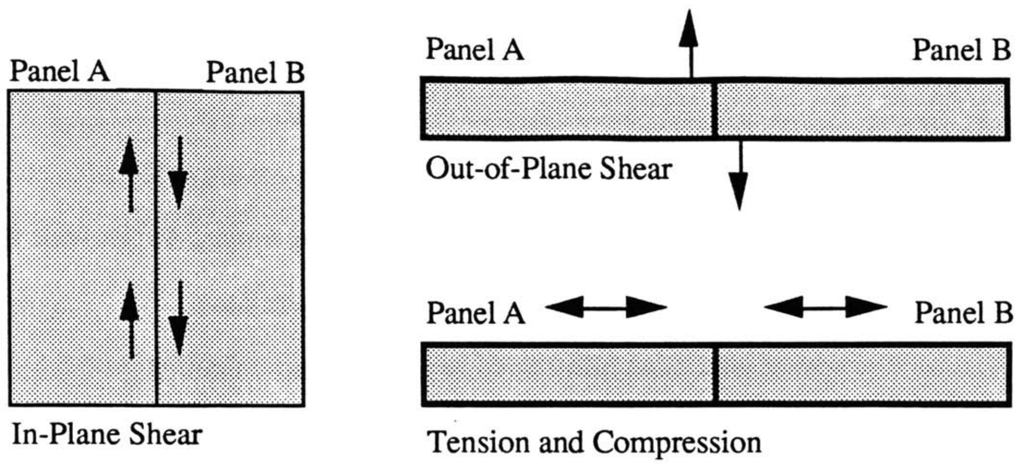

Figure 6.6 : Structural requirements of the panel-to-panel joint

• The corresponding joint in standard rafter or truss construction is the sheathing edges nailed to the rafter or truss. This is an extremely simple and inexpensive joint.

• Long sections (panel length) of the joint are connected at once, making strenuous ease of assembly demands.

• Unlike other joints, both elements to be connected are in the same plane. The luxury of using the third dimension outside the panel width is not available.

Using this third dimension is contrary to the flat planar nature of the roof (inside & out). Other joints incorporate a change in angle or material such that additional detailing in the form of connection hardware is not objectionable. For example, at the ridge a projecting beam is expected and even desired because people have a natural sense that there should be some form of visible structural support there. At the panel-to-panel connection there are structural requirements (as described above) but they are not obvious to the layperson. Moreover, the prejudice against prefabrication often derives from the obvious appearance of panel-to-panel seams.

The cam-lock concept:

The panel-to-panel joint design proceeded along two distinct paths. One was the tapered spline as described below. The other was the cam-lock joint. This joint was originally inspired by the Chase Thermo-Panels (section 3.6) cam-lock joint. The manufacture of these panels was halted because the increased convenience they provided the builder did not translate into savings for the owner[3]. We felt that the Chase panels did not take full advantage of the opportunities the cam provided - particularly increased finish on the panels. Cam-locks appeared attractive for the roof panel system because the minimal interference with the panel surfaces meant that they could have an increased degree of finish applied in the factory. In theory, they are very quick and easy to assemble.

Problems were discovered with the cam mock-ups built in the lab, however,. The cam panel fasteners available were too small compared to the size of the roof panels. It became apparent that alignment of the cam arm and pin, both in-plane and out-of-plane of the panels, would be difficult. The Chase cam panels were lighter and they were wall panels where out-of-plane alignment was not a problem. The cam-lock concept was abandoned in favor of the tapered spline panel to panel joint.

The tapered spline concept:

The design process led to a concept that is similar to the existing technology of the thermal spline (figure 2.6), with two modifications. The first modification is to taper the spline edges and the edges of the panel to allow easier fit and alignment. Ideally, both male and female sides would be tapered to the same angle so there are no voids in the structural joint. Screws hold both pieces of wood tight against each other. In the proof-of-concept

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[3]Communication with Winter Panel Central (formerly Cheney Building Systems)

structure, however, only the spline edge will be tapered and there will be a slight void at the corners of the spline cavity (figure 6.7). The second modification is to provide channels through the spline core to allow ventilation to continue across the panel-to-panel joint.

In order to accommodate thermal and hygroscopic movement of the panel faces as mentioned above, the spline should be slightly wider than the spline cavity. This will provide a slight gap (1/8" to 1/4") between panel faces. The panels must be reduced in width by this amount to maintain the 4' spacing.

An alternative concept is to have compressible foam in the spline, eliminating the fitting and tolerance problems associated with the rigid spline (section 5.2). This spline would still need to have slightly beveled edges for alignment, and would also be vented.

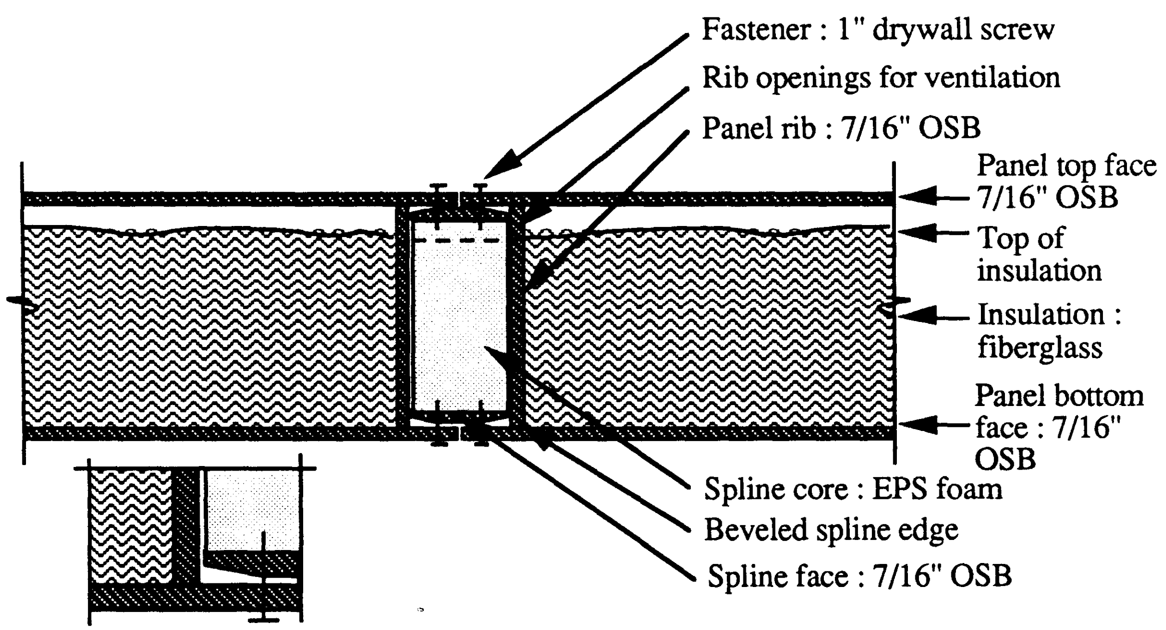

Figure 6.7 : Tapered spline panel-to-panel joint

6.3.2 Ridge joint[4]

The ridge connection has the same basic structural requirements as the eaves: vertical support, uplift resistance, and sliding resistance (shear). The major difference between the ridge and the eave is that the ridge is not continuously supported by a wall. Ideally, it should span a considerable distance, thereby reducing the interruption of the usable space by columns.

Given the previous decision for a ridge beam (section 4.1.8), the ridge joint has three basic elements: the fastening method, closure of the seam to the environment, and the design of the ridge beam. Because of tolerance considerations, it was decided to register the panel and do the initial fastening at the ridge (section 5.2). The remaining two elements of the ridge joint are elaborated on below.

Closure of the seam at the ridge line:

The ridge joint at the panel ends can be square or beveled. The advantages of the square-ended panel include easier manufacturing, less fragility, potentially easier alignment, and more forgiving tolerances on the manufactured parts. Also, square-ended panels are non slope-specific. The advantages of the beveled panel-end include a smaller gap to fill with the ridge cap, and potentially better performance in insulating, sealing, etc.

Beveled panels were chosen for use on the proof-of-concept structure. The improved performance of the ridge joint seemed important, and by registering panels at the ridge, it is easy to meet the attendant close tolerance.

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[4]A more detailed structural analysis of the roof panel and ridge beam is contained in [Morse-Fortier, 91]

Design of the ridge beam:

The design of the ridge beam must facilitate the first two elements, or purposes, of the ridge joint (fastening and closure) as easily as possible. Towards this goal, the ridge beam is a triangular-shaped, reinforced box beam, whose angles conform to the slope of the roof

The reasons for electing to use a ridge beam were described in section 4.1.8. Wood was chosen over steel for reasons of material, assembly and fastening consistency throughout the system; and due to uncertainty about whether steel could be formed into the proper shape for panel assembly at a reasonable cost. The wide, triangular wood section carries many advantages. Its lateral and torsional stiffness make it ideal for use as an assembly platform: even if panels are installed on only one side, the ridge beam will not deflect unacceptably. Also, its width makes it easy to walk and sit upon. Keeping the beam hollow is natural and logical as stiffness is increased by moving material toward the outside of the beam section and the enclosed volume can be further exploited for utilities. Also, as it evolved, the ridge beam began to emerge as an opportunity for a component that can serve multiple functions.

The first version of the ridge beam called for small triangular wood trusses sheathed with 2 layers of 7/16" OSB (or other panel material - plywood, etc.). Sheathing would be complete on the 2 sloping sides and partial on the bottom (figure 6.10a). It carries loads mainly through the of shear stiffness of the sloping OSB faces, and in tension in the OSB on the bottom of the beam. The effective EI of the beam is 2.24×10^9 in.^{2} lb.. A half scale model of the beam was tested to failure in order to learn about the design. The model was 8 feet long, supported at the ends and loaded at the quarter points. It failed at 3575 pounds by splitting a corner of the end truss in shear in the direction of the beam (out-of-plane of the truss). This mode of failure underscored the fact that the only way to transfer the shear from the side faces to the bottom faces (which act in tension) was through the discontinuous trusses. The trusses were not able to carry such large out-of-plane shear across the truss plate connection.

The second version attempted to cure this problem by replacing the trusses with solid wood sections (or gluelam, paralam, LVL, etc.) in the 3 corners of the beam. In this design, shear would be transferred continuously between the faces. These sections run the length of the beam and are referred to here as 'corner-wood' (figure 6.10b). In addition to transferring shear, they boost the moment of inertia of the beam. The corner-wood pieces are located farthest from the neutral axis of the beam where they contribute the most to its moment of inertia. They resist loads in tension and compression, which is what long pieces of wood are best suited to. Wood cross-members bridge the gap across the bottom faces to hold the triangular shape of the beam.

The effective EI of this version is 5.21×10^9 in.^{2} lb. A half scale model of this version was tested in the same manner as the first one was. It failed at 2200 pounds. This lower failure load is attributable to the elimination of the trusses. In removing the trusses, we failed to adequately consider their third dimensional effects in resisting beam loading. In the first version, the sloped truss chords carried compression loads from the top (peak) of the beam (where loads are applied) down to the corners to be resolved in tension in the bottom chords. In the second version, this load was carried down through the OSB faces and had to be transferred into the corner-wood through shear in the glue-screw connection. From the corner-wood it could then be transferred into the bottom faces and then into the cross-members, where it would be finally resolved in tension. Here, the glue-screw bond failed at the corners, where this load is greatest, causing the beam to spread apart. The trusses had been doing two things; one for which they were poorly suited - longitudinal shear transfer, and one for which they were ideally suited - tying the section into a coherent three dimensional structure.

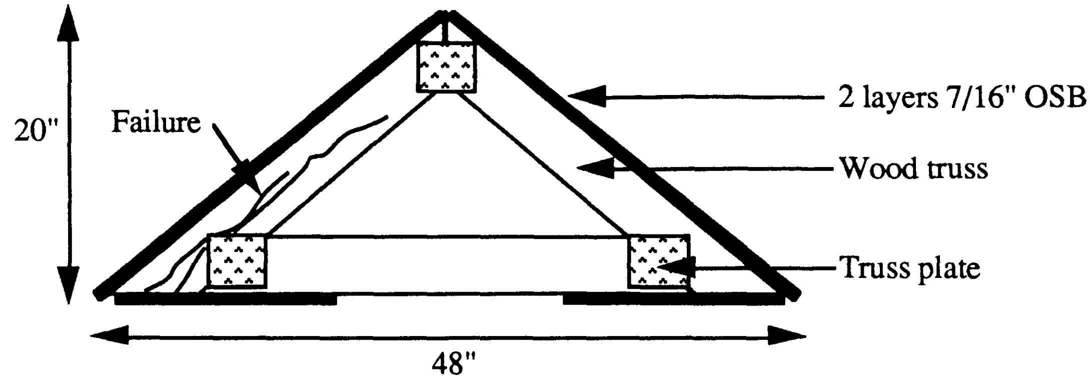

Figure 6.10a : Ridge beam version 1

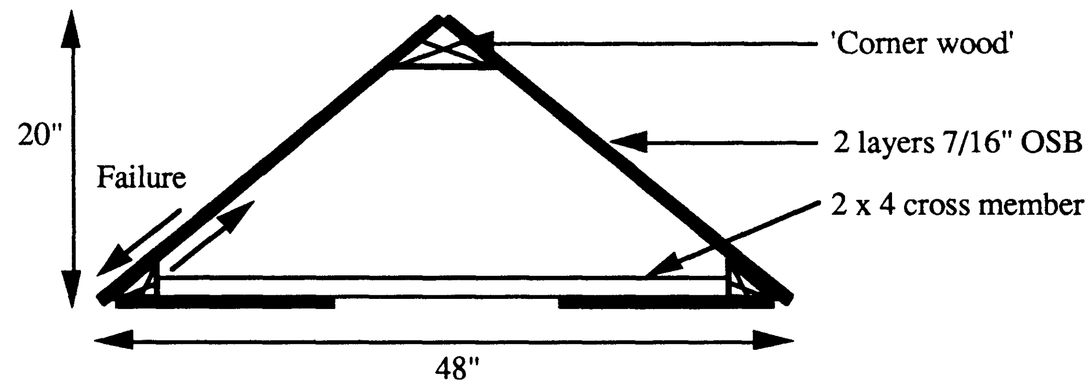

Figure 6.10b : Ridge beam version 2

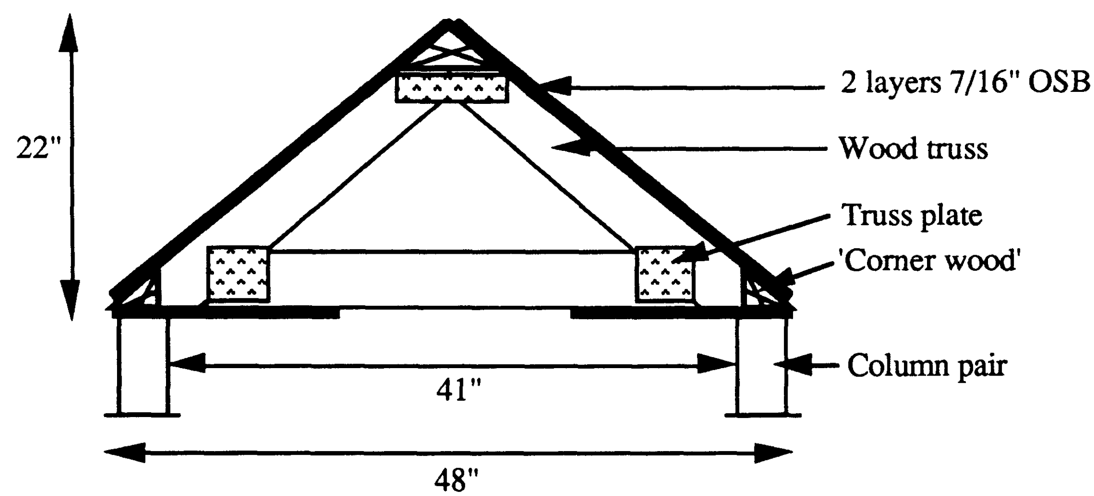

Figure 6.10c : Ridge beam version 3

Figure 6.10 : Ridge beam concepts designed, developed, and tested at half scale

The third version of the ridge beam (figure 6.10c) includes both the trusses and the corner-wood. The trusses, however, are placed only at points of concentrated load (i.e. bearing and loading points) where the outward thrusting tendency is greatest. Its depth was also increased to 22 inches by sliding the lower corner-wood pieces down to the edge of the sloped OSB sheathing sides. This was done not just to increase the moment of inertia (which it does), but to allow the supporting columns on either side of the beam to move farther apart and still remain under the corner-wood. It is desirable to permit clearance for a doorway between the pair of columns. The effective EI of this beam is 6.47 x 10^9 in.^{2} lb. A half scale model of this version was tested identically to the other two. It failed at 7440 pounds exhibiting both previous failure modes, either simultaneously or in sequence. Just before failure the maximum midspan deflection was .405 inches. Accounting for contributions from bending (.261 inches), shear (.070 inches), and deformation of the truss (.061 inches), the predicted deflection is .392 inches. This small (3%) difference between predicted and observed deflection is probably attributable to localized crushing at the supports.

Given the limited number of samples (1) and the uncertain nature of a complex configuration of a natural material held together with both chemical and mechanical fasteners, this successful test cannot be considered conclusive. All tests conducted on the ridge beam were part of the design/learning process. They do not represent a statistically significant sample, nor are they an attempt to establish load carrying capabilities of the final member as designed.

The final design of the ridge beam for the POC structure (figure 6.11) attempts to use all materials and components in their most effective manner. The OSB sheathing is primarily used as a shear web. The corner-wood acts in tension and compression and is braced against buckling by the OSB. The trusses act as roof trusses in preventing the spreading tendency of the triangular shaped beam. They will be placed on 4 foot centers and doubled at the supports to further stabilize the shape of the beam and resist local deflection at the ridge ledger loading line. For use in the POC structure, the ridge beam is four feet wide at the base and 22" deep. These dimensions are based largely on geometrical constraints. For this case its primary span is as shown in figure 6.12.

The maximum span of this beam within the context of the roof panel system can only be estimated case by case. Using the maximum panel span of 19.4 feet (measured horizontally) yielding a house width of 40' (section 6.2) and a one foot eave overhang, a distributed load of 40 psf results in 850 pounds per linear foot (plf) along the ridge beam. This assumes no concentrated loads due to intersecting ridge beams, hips, etc. are present. Using the effective bending stiffness EI from above, and shear stiffness AG (5.94×10^6 lb.), the maximum simple span, as governed by live load deflection, is:

$$\delta = \frac{5\omega L^4}{384\,EI} + \frac{3\omega L^2}{20AG} \leq \frac{L}{240}$$

$$\frac{1}{240} = \frac{5\,(850)\,(L^3)\,(12)^2}{(384)\,(6.47 \times 10^9)} + \frac{3\,(850)\,(L)}{(20)\,(5.94 \times 10^6)}$$

Solving for L yields 24 feet. This is long enough for use in an average house if one intermediate support is used. For a smaller 24 foot wide house, the tributary area of the ridge beam is 13 feet (including an overhang), yielding a load of 524 plf. In this case the span of the ridge beam is extended to:

$$\frac{1}{240} = \frac{5\,(524)\,(L^3)(12)^2}{(384)\,(6.47 \times 10^9)} + \frac{3(524)\,(L)}{(20)\,(5.94 \times 10^6)}$$

Solving for L yields 29'-3", which is long enough to clear-span a small house.

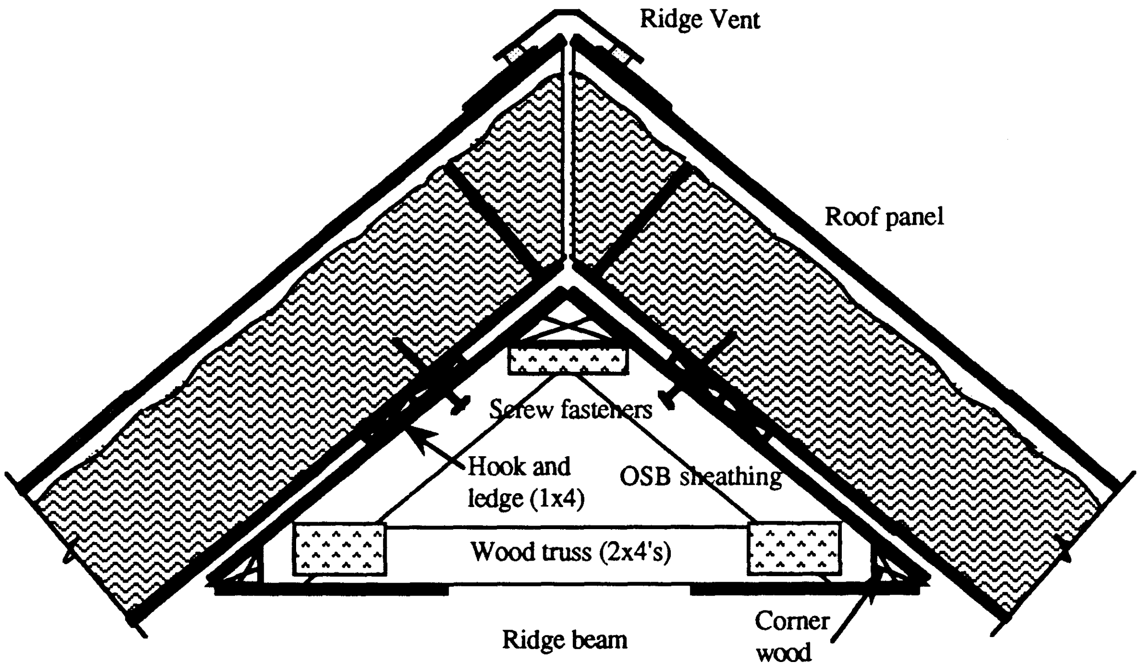

Figure 6.11 : Ridge detail

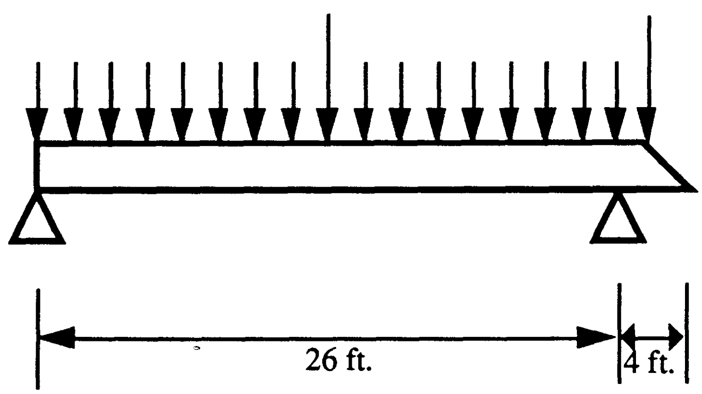

Figure 6.12 : POC ridge beam loading

Advantages of the ridge joint:

The beam can be reached into from underneath to fasten through to the panel along a hook on the bottom of the panel. The space within the hollow beam can also be used for recessed lighting, insulation, ductwork and other conduits. The underside of the beam is ideal for the installation of sheetrock. Drywall tape joints are minimized and acute angles, often needed to cover beams, are eliminated. The method of support and fastening the panels does not disturb their ends, enabling the system to retain the option of having square or beveled panel ends.

An additional structural advantage of the open-truss ridge beam is its stiffness in resisting lateral loads. This capability reduces the in-plane shear requirements of the panel-to-panel joints by lowering the amount of diaphragm action required of the roof planes.

One question remaining is the applicability of this ridge beam to a shallow pitched roof. In that case, the ridge beam may take on a pentagonal shaped to prevent it from becoming unreasonably wide.

6.3.3 Valley and hip joint

There are three strategies that the valley and hip joints can be based upon. First is a beam supporting the panels along the length of the joint. This is consistent with a ridge beam strategy and makes panel assembly easier. However, to enable simple beam end connections and to not encroach on the interior space, steel is the only appropriate material for the beams. This is costly. Also, framing the roof in this way fails to use the panels to their fullest structural potential. Since the stiffer load path in the constructed building will most likely be tension across the valley or compression at the hip joint and not bending in the beam, the beam will be useful only during assembly - a very expensive method.

The second strategy is to tie (with a steel strap) each valley and hip panel to the panel opposite it across the valley or hip line. This, however, is inconsistent with the ridge beam strategy. Also, it requires temporary support during construction which runs contrary to the speed of construction design goal.

The third strategy is to assemble the valley and hip panels together on the ground into large triangles. In the POC structure, these triangles will contain 3 or 4 panels and weigh about 650 pounds. Each section can be assembled on the ground, if it is flat enough; on the floor deck, if space permits; or on saw horses. The assembly is then lifted into place on the roof. It will be supported along one edge (ridge if valley, eave if hip) and at one additional point (eave if valley, ridge if hip). Also, it will be supported along a second edge once the adjacent panel (or gable-end wall) is in place. This strategy depends on the panel-to-panel joint providing some rotational rigidity. The support conditions and stiffness of the spline joint make this strategy possible. The simplicity of the resulting valley and hip joints, and the attractiveness of ground assembly make this strategy desirable.

Using this strategy forces us to worry about the crane lift of the assembled triangle. With careful attention to the positioning of lift points and by incorporating steel members into the crane rigging if need be, the bending moment on the spline connections can be reduced. Some foam-core panel builders pre-assemble large sections of roof in this way and lift them into place without additional stiffeners[5].

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[5]Advisory Board

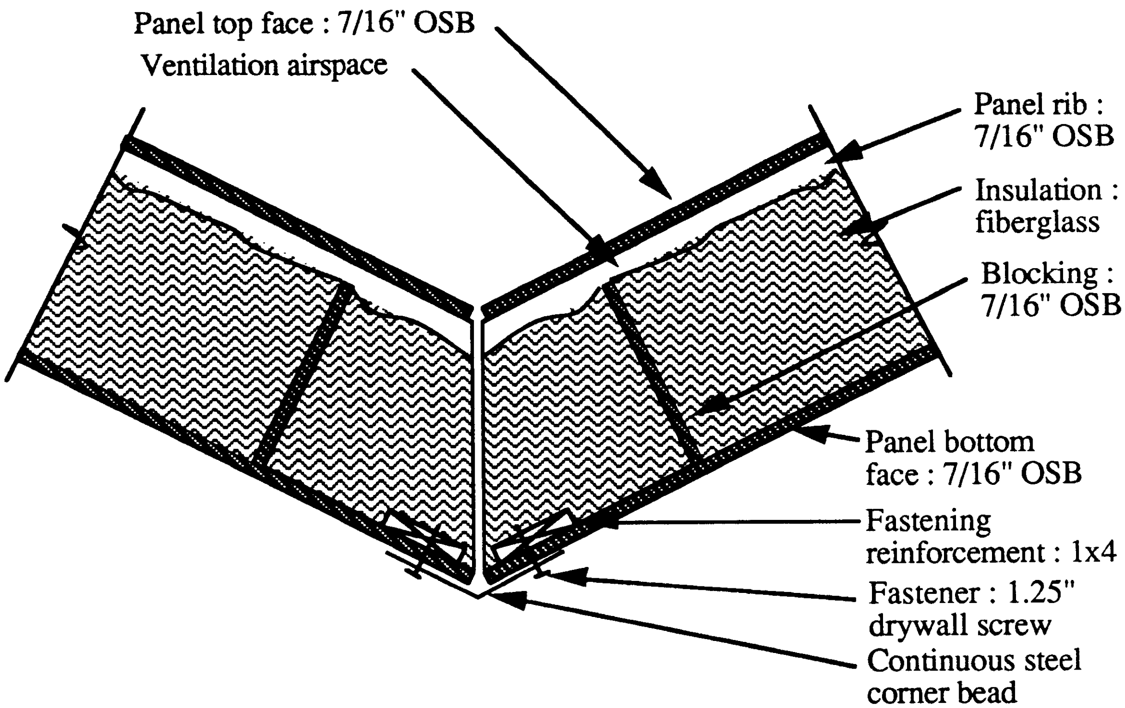


Figure 6.10 : Valley detail

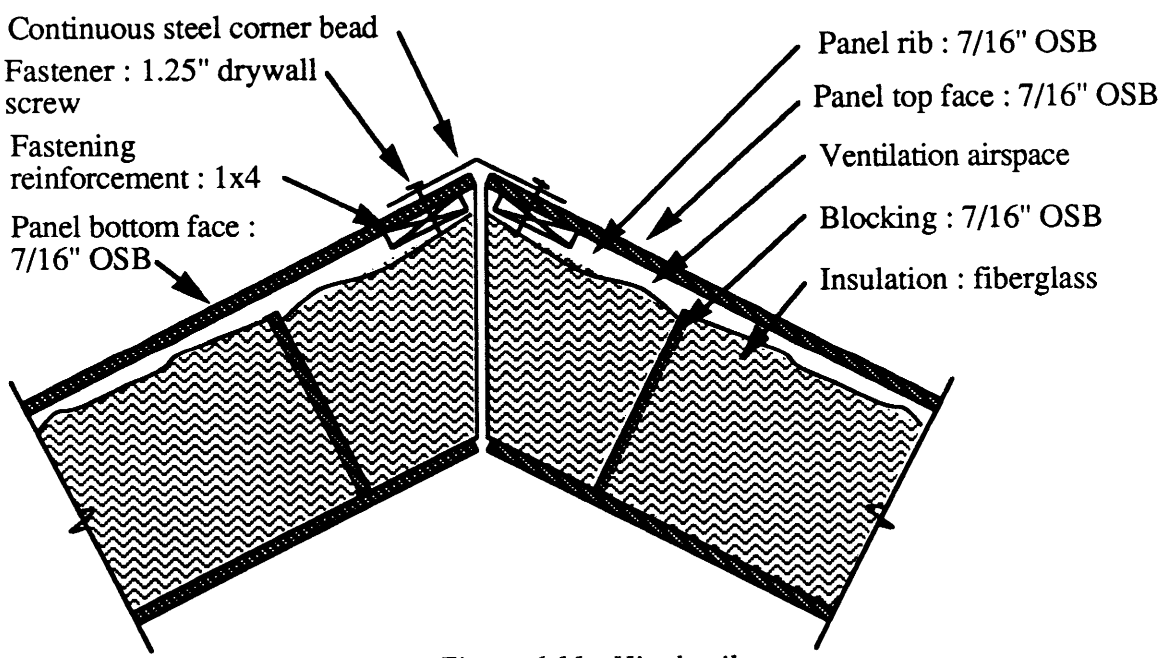


Figure 6.11 : Hip detail

CHAPTER 7 Implications of the System

7.1 Implications for architectural design

In designing the panel system, considerations of architectural design were approached from the point of view that a building system will face easier acceptance if it does not radically alter the way houses are designed today. This holds true for both the design of the final product and for the design process itself. The roof system is designed to be able to build most architectural forms common among today's production built houses (section 3.1). To accommodate that which it cannot do, an important feature is that it be compatible with conventional construction (section 3.11).

Given that any building system, either prefabricated or site-built, has definite characteristics, certain building forms will enable the panelized roofing system to be used more efficiently. It is expected, and hoped, that this family of architectural forms and space usages would naturally come to be prevalent among houses using this system. The system may affect the house dimensioning, space usage, roof pitch, service integration and roof aesthetics. This section will attempt to project what these forms and implications might be.

The roof panel system is prefabricated and is therefore less site-flexible. This will, by necessity, force the designer to pay more attention to the roof in the initial stages of design. The layout of the roof will become an important consideration. It must be logically thought out and designed for efficiency before it is sent off to be fabricated. As a result, the roof will be more ordered and deliberate than if designed under the assumption that an infinitely flexible, site-figured-out building system is being used. The designer, for good or for bad, will not be able to design a house in plan and then let the gables run about and collide as they may.

The manufacturing strategy of the panels is based on a 4 foot module for the standard panel (section 4.10). This size module will be the most cost efficient to produce. This economy of size will affect the dimensioning of a house. The house will gravitate toward a 4 foot module in the direction of the ridge line, corresponding to this standard panel width. It has been shown that the imposition of a four foot wide wall panel module on common house plans will not cause undue disruption in the design or excessive wasted space inside (section 4.1.10). Compatibility with conventional stick-frame construction allows the designer to liberate the house from this restriction at places in the design or in later additions/renovations. Also, variable rake and eave overhangs enable the house dimension to be somewhat free of the roof dimensions.

A major advantage of using insulated roof panels is the usability of the roof cavity space. With roof trusses, this space is often not usable, or severely restricted if attic or scissor trusses (figure 3.1) are used. Rafters without a ridge beam necessitate tieing the two sides of the roof together with an attic floor or collar ties. Both of these elements can impose restrictions on the space usage. In addition, attic-floor tied systems often have the insulation placed on the floor, leaving the roof cavity outside of the building thermal envelope. The panel system enables complete freedom of use in the roof cavity space. This feature is expected to be a major selling point of the system. It will be important to take advantage of this space, either as living space or a cathedral ceiling, for the system to be most cost effective.

The pitch of the roof may also be affected by the panel system. Truss and collar tied rafter systems function better at steeper roof pitches for structural reasons, but often are denied since the roof cavity space will be wasted. Panel systems, in general, do not call for steep roof pitches for structural reasons (the ridge beam obviates the need for deeper truss action) but must be steep in order to take advantage of the usable roof cavity space they provide. The open truss ridge beam (section 6.3.2), used in the panel system is more structurally efficient with steeper pitches. This aspect of the system does call for steep pitches, but the panels could still function well in a shallow pitched cathedral ceiling (here, however, a different ridge beam might be preferred). Overall, one would expect the roof panel system to be used with steep pitches to take fullest advantage of the roof cavity space.

Coordination and construction of penetrations through prefabricated roof panels may be difficult if site-alteration and off-line manufacturing of components is to be minimized. A strategy consistent with componentization and with the advantages of the stick-frame method of construction may be to accommodate roof penetrations by clustering them in a conventionally framed infill section between panels. This could have far reaching implications on the layout of the house. Vent stacks, electrical feeds and flues/chimneys are services that often pass through the roof of a house. The grouping of these services below the penetration area leads naturally to a centralized mechanical core area. This in turn could spur the use of prefabricated wet and mechanical core units in conjunction with the panel roof system. Conversely, the core units may encourage the use of a panelized roof system.

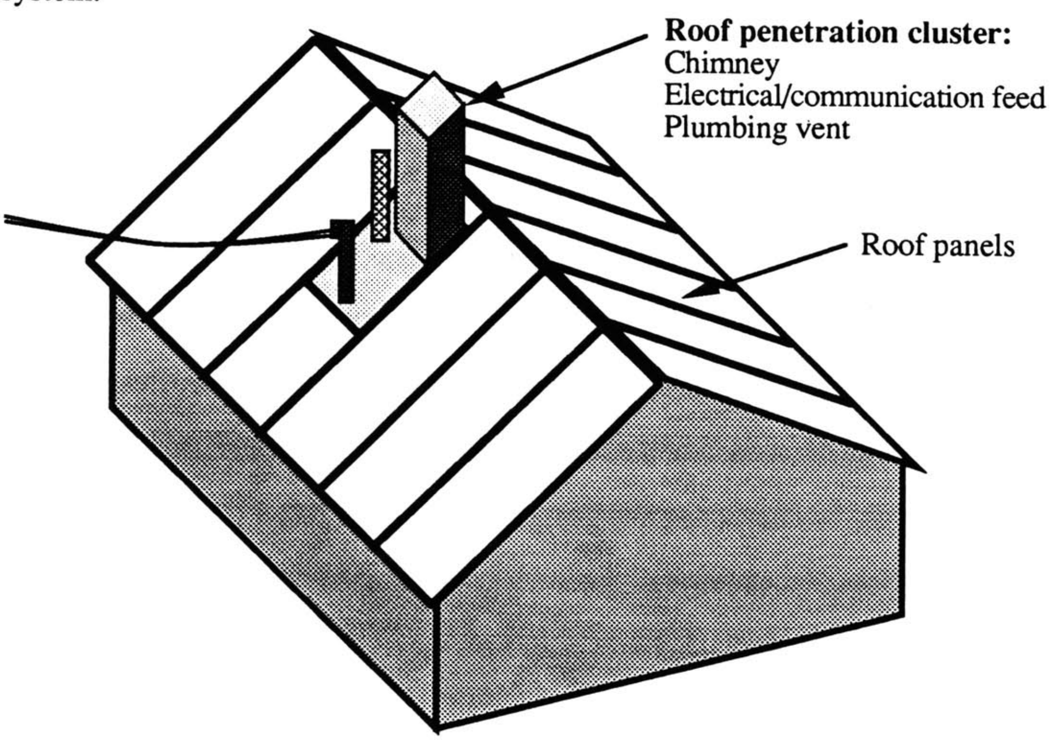


Figure 7.1 : Clustering of roof penetrations

In addition to penetrations, the panel system may encourage certain ways of service distribution within the roof cavity and by extension, within the whole house. The hollow ridge beam is ideal for carrying power lines and ductwork along the length of the house - indeed, this was designed to be one of its main features. It also provides an ideal location for mounting recessed lighting and HVAC registers for the usable space in the roof cavity. The ridge beam sub-system calls for bringing all the services up through one of the supporting walls or columns, laterally along the length of the house through the ridge beam, and down the panels themselves to outlets, fixtures and communications jacks (figure 7.2). Ease of service distribution within a habitable roof cavity space will probably result in a highly finished living space at time of construction or at the time of later renovations.

The roof panel system, while not necessarily demanding it, may lend itself to new distinct styles of aesthetic detailing by the designer. These may include exaggerated overhangs at the eave and gable walls and new ways of trimming the roof at the rakes and eaves. One example is to have square panel ends at the eaves instead of cutting the eave off vertically as is usually done with rafters. A gutter system built-in to the panels may make this possible (appendix A.1.1).

One potentially exciting visual effect could be to reveal the panelization in the pattern of the roofing material. This strategy could make the panel-to-panel seams an architectural design feature. A four foot on center pattern of joints, or a more frequent spacing if combined with the pattern of the roofing material, could result in an attractive roof design and it would facilitate pre-roofed panels much easier than a scheme where one tried to conceal the joints. An example of this strategy is the standing seam or batten metal roof concept described in appendix A.1.2.

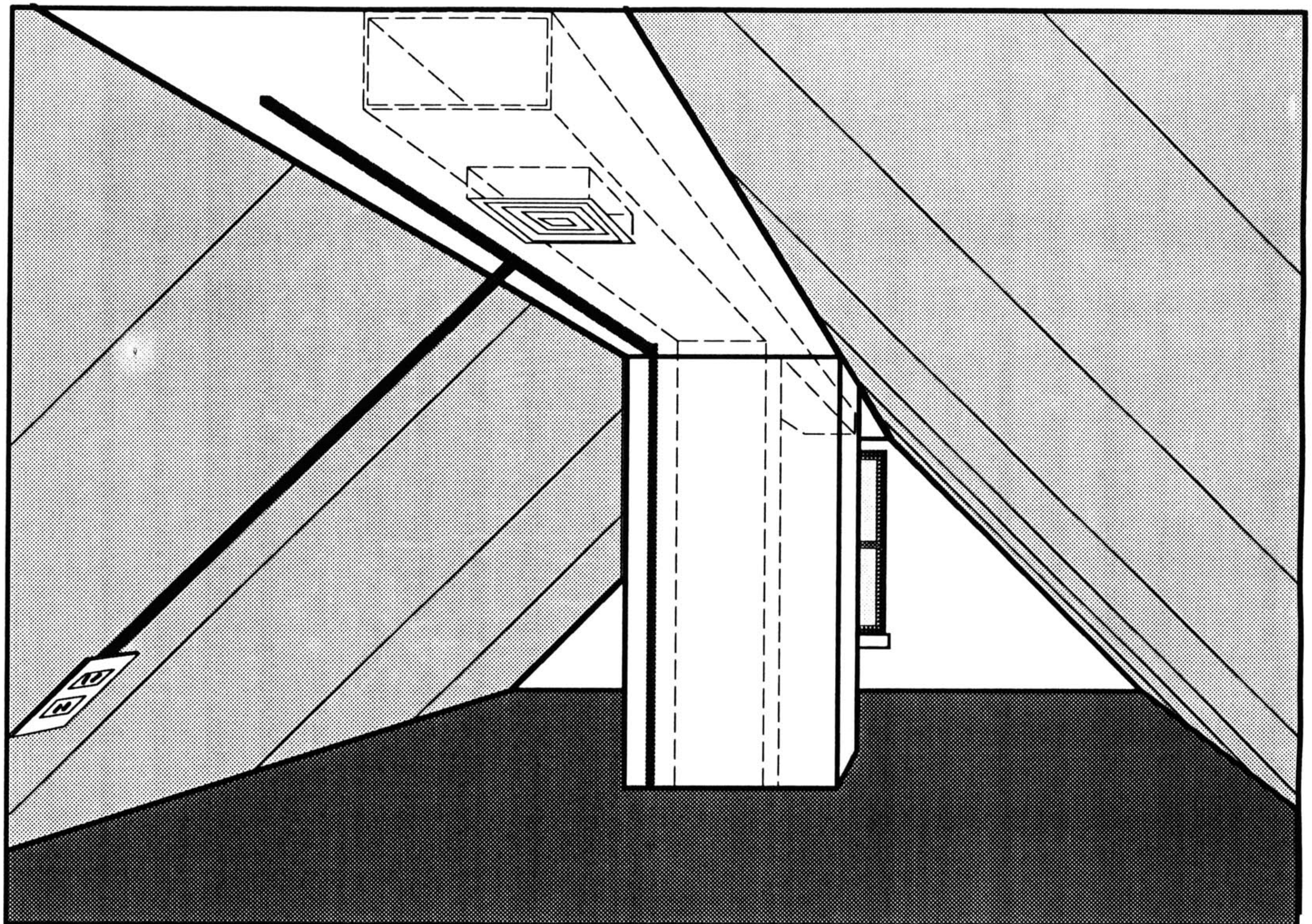


Figure 7.2 : Service distribution within roof panel system

7.2 Implications for the design and construction process

This section briefly suggests some scenarios that can be envisioned for the design, distribution and erection of a house employing the panel system. The author is neither a marketing specialist, nor a housing industry analyst. Some of these scenarios may seem simple or even naive, however they are included because they have influenced decisions regarding the design, manufacture, transport and erection of the roof system.

One scenario imagines the panel system as a typical component playing a role consistent with a traditional custom designed or production built home. Here, as in traditional componentization, the panel fabricator would be the supplier to the builder who erects the panels. This scenario is simplest to initiate but places the panel fabricator at the mercy of the builder's capabilities and attitudes . This implies severe limitations on the way in which the system can change the way that on-site trades function and the way the house is built.

In another scenario the panel fabricator would be a subcontractor to the general contractor. The panels could be erected by the fabricator's own forces or by specially trained and contracted crews. The component producer takes the responsibility for manufacturing *and* installing the roof system. In this scenario, the panel fabricator has moved one step up the value chain to the position of subcontractor. The panel-maker no longer need worry about the general contractor's knowledge of panelized construction (except that the building walls meet the required field tolerances), but now faces the added difficulty of maintaining a network of trained and equipped erection crews. The major advantage is that quality installation and therefore the panel system's good reputation can be better ensured.

A third scenario may have the roof panel system integrated into an overall building system, including the walls and foundation. In this case the entire system could be sold as a package including design services. This scenario is close to resulting in a fully prefabricated house, and so runs contrary to our strategy to combat the negative perception of prefabrication as explained in section 3.4. For an all inclusive building system to work, it must be certain that disadvantages of one part of the system do not negate the advantages of another. This is why the decision was made to focus on one part of the house - the roof - where a need was seen.

For any of these scenarios, when designing the house, the designer should be aware of the building system being used. This is true for any building system. If the designer is independent of the panel fabricator, an exchange of shop drawings and approvals, as is customary with roof trusses, will be necessary to ensure the correctness of the panel fabrication. The fabricator must have adequate time between shop drawing approval and roof erection in which to fabricate the panels.

CHAPTER 8 Evaluations and conclusions

8.1 Evaluation of the design process

This section evaluates the design process used to develop the roof panel system. It describes some of the problems encountered in a group design process and how the organization of the process and certain design tools may be used to cure them. Finally, the use of the Pugh Method to design the roof system joints is discussed and evaluated.

Some form of organization of the design process is important. Solely tossing out ideas and bouncing them around is good to start off with and to get the creative juices flowing, but soon a leader or structured method must enter the game. A good method of organization helps speed up the process, bring out new issues and ideas and reduce the amount of looping back and forth. It is particularly important if working in a large multidisciplinary group, especially if the participants have not worked together before.

One danger that exists in any design process, and occurred in our case, is that of "undead concepts". This is the problem of concepts that were once discarded by the group, coming back to life repeatedly. This may happen without any new facts or ideas emerging to justify their revivification. Possible reasons for this occurring include:

• A lack of understanding by some participants of the reason the concept was discarded by the group.

• A lack of record of the design concept and reason for its discard, and subsequently the group's forgetting of that reason.

• A sense of ownership by some member of the design team, and the apparent appropriateness of the scheme within a specific discussion.

These problems prevent the quick dismissal of an unjustly revived concept, but why does it get brought up again to begin with? The concept is most often revived by its originator. People get emotionally attached to their ideas - they think that a rejection of the idea is a rejection of them. When someone falls into the trap of becoming emotionally attached to a design concept (or "married" to it), they become constrained by it. Their arguments all stem from the one concept and the criteria list may become influenced (or contaminated) by it. In order to halt this "concept creep", participants must become aware of the many different concepts and solutions possible.

It is much easier to make someone give up an idea if you can show them some form of physical or written evidence that they can not ignore. Although the spirit of the Pugh process is not to shoot down ideas, it does provides a matrix sheet that serves as such hard evidence to do just that. It points out characteristics and specific reasons for the inadequacy of a concept, in terms of the agreed-upon criteria list. Also, the matrix forces people to concentrate on the issues and to not get emotionally involved or sidetracked.

Any design team, particularly a multidisciplinary one, must confront the issue of a lack of expertise within the group. It is unlikely that any group will have all the areas of expertise satisfactorily covered. The formulation and use of a design criteria list can help the group come to grips with this problem. In a complete and concise list of criteria, all areas of knowledge necessary for the design should be represented. The first pass through the list with a set of concepts will bring to light the areas of expertise the group should have. The list makes it easier to convince the group and thereby establish that some specific knowledge does not exist in the group. This understanding is important so that assumptions, questions and evaluations in these areas will be later understood in this context. The group may also consider bringing in outside consultants.

The order of the criteria on the list is important as it can help make the discussion flow in a logical manner. A well thought out order can help prevent confusion and wasted time. Broader issues (ex: 'ease of alignment') should go before specifics that depend on them (ex: 'skill level required') since the broad issues will be discussed any way if they have not been reached yet. If the broad issues have been decided upon, the specifics will go that much quicker. The order is also important when dealing with related criteria as they may naturally occur. For example, 'potential for damage' should come before 'repairability'. As the group develops the criteria list, it should also consider this order.

It seems better not to enforce a rigid design method on people, especially at the beginning of the process. Designers need the flexibility to work in their own style at their own pace. By forcing them into a structured method, their creativity will likely be stifled. The concept of using certain design methods as tools to be used at points in the process seems attractive. This allows the design process to remain flexible and spontaneous. These tools may be put into use by either an overseer of the process or by group consensus. Reasons for activating a design tool include creativity stagnation, the designers losing sight of their design criteria, when issues can not be decided by consensus, or for tasks such as concept selection, elimination and hybridization. Additionally, design tools may be activated to combat the problems of concept revival and lack of expertise as described above.

By the fourth joint, the valley joint, the group did not go through the formal Pugh process. We were so used to the criteria, the process and its goals, that after 6 sessions and 3 joints, the concept generation, synthesis and refinement all happened automatically. The advantages and disadvantages of each concept were apparent without the formal comparisons being done. At this point, the design tool was not needed. Halting the discussion and forcing the group to go through the list of criteria would have been a stifling act.

The previous design decisions speeded up this session on the valley joint since they restricted the range of solutions possible. The result was a well designed joint consistent with the previous decisions. This illustrates the importance of carefully choosing the order of joint design. It also reveals that good decisions were made in the earlier sessions and in the earlier system decisions.

A problem with the design method was to keep the participants and the process disciplined. When things are going well there is a tendency to feel that the structured method is no longer needed. It is possible to relax the method as described above, however, one never graduates from needing it. We fell back into the same old traps shortly after relaxing the method.

In the beginning, our project experienced both the problems of reviving concepts and lack of expertise. We had poorly defined design criteria (the attempt to organize a criteria list had not been made yet) and we lacked expertise in mechanical and structural engineering. The introduction of the Pugh process worked well for us. The record formed by the matrix sheets put discarded concepts to rest for good. The personalization of concepts was reduced by having all concepts presented by the same person after gaining input from other people on their ideas. This helped in preventing everyone from pulling for their own ideas at the expense of objectivity. The expertise problem was corrected, and as additional areas of missing knowledge surfaced, the design selection process and the criteria list helped us become aware of them.

8.2 Evaluation of the roof system

Unfortunately, the proof-of-concept structure was not completed in time for a full evaluation to be included in this thesis. However, some initial evaluations are possible regarding the panel itself.

The rib-panel glue bond, aided by the staples, holds well and the panel is maneuverable directly after stapling. Quality control is very important. In cutting and assembly, two key dimensions that must be watched constantly are the rib widths and the spline cavity depths. Rib widths must be kept to within plus or minus 1/16" of the 9 1/4" width. The ribs must be watched so they remain perpendicular to the faces and run straight. The blocking aids in the former, but blocking pieces must be fitted very closely since slight variations in rib spacing do occur (+ or - 1/8"). Some problems in meeting these tolerances are most likely symptomatic of the prototype scale manual manufacturing process being used. Overall, the panels go together smoothly and appear quite stiff, both in the long direction, and once the glue sets and aided by the blocking, in the cross direction as well.

Beyond this, until the proof-of-concept structure is erected, no further evaluation of the roof panel erection and performance can be made. A full evaluation will be published upon its completion.

8.3 Conclusion

The roof panel system has been designed for flexibility, for efficient use of materials and labor, and for superior performance at a reasonable cost. A ribbed panel was chosen because it allowed the use of materials that were most cost efficient in their applications based on the short-term research time horizon. OSB was selected as the primary structural material for the roof panels for its good physical properties, its availability in large sizes, and because it is relatively inexpensive.

The roof is a prime target for innovation because it is one of the most difficult parts of the house to frame conventionally and is a critical step on the path to getting the house 'tight'. Stresskin panels are ideally suited for use as a strategy for innovation in the context of componentization of the roof. They can be custom manufactured to accommodate architectural design flexibility, efficiently transported and erected and may be compatible with conventional stick frame construction.

Componentization of U.S. residential construction is a longstanding trend. Its overall effect is to reduce 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 and large development tracts, the rising cost of traditional building materials and componentization's advantages as an open building system. Components represent the best way to reduce the cost and increase the quality of housing.

APPENDIX A Additional design ideas

This section contains additional design ideas, falling into two categories:

• Additional features of the panelized roof system.

• Alternative design concepts considered.

A.1 Additional features

The additional features for the roof system presented here are meant to illustrate the expanded potential of the roof system and explore some ideas for possible future research and design work.

A.1.1 Built-in gutters

A prefabricated roof panel system provides opportunities to prefabricate other parts of the house and include them in the same product. It may be advantageous to include those elements that share physical location with the roof panels but may have a separate function.

One such part, or sub-system, that is present on many houses, is the gutters. The gutters are usually attached to the fascia board on the eave, and to make this easier the rafter ends are usually cut off vertically (figure A.1). Figure A.1 also illustrates a conventional eave with gutter and the built-in gutter concept. In the built-in gutter concept, the end of the panel is notched to allow a pre-formed gutter to be let in. Leads can pass through the panel where they emerge at the soffit. This concept provides a more durable gutter system, less obtrusive leaders, and simplifies the eave trim detail by allowing square ended panels.

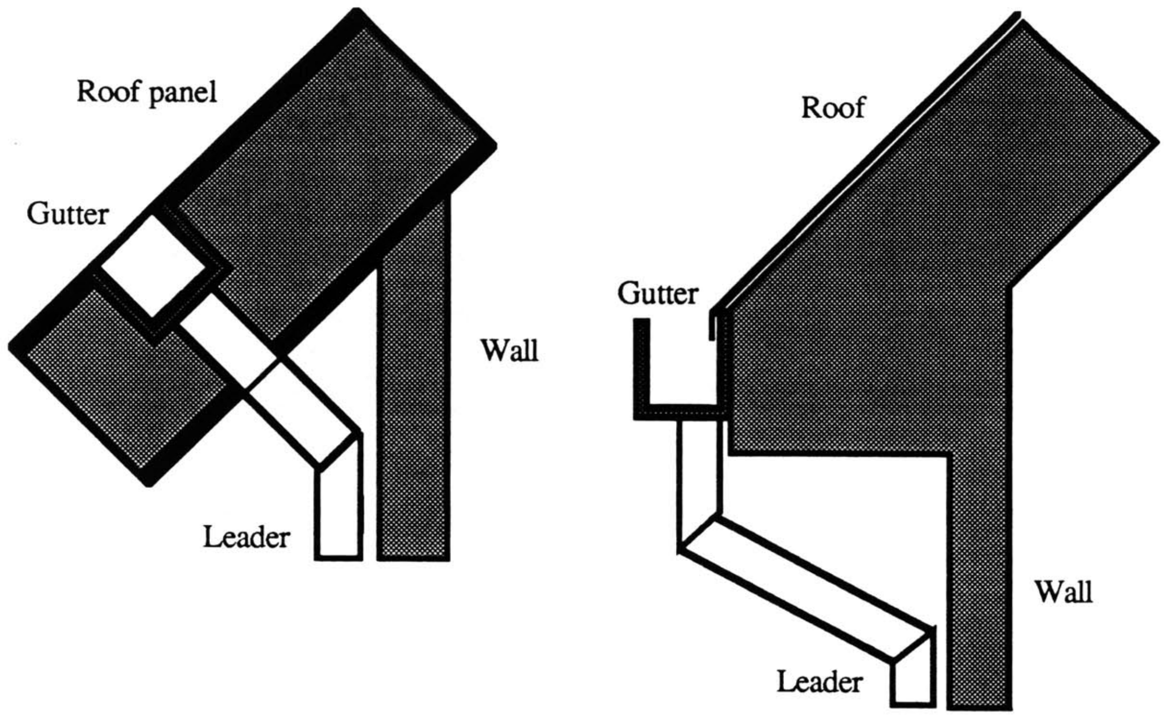


Figure A.1 : Gutter built into panel and conventional gutter

A.1.2 Metal roofing in conjunction with roof panels

As a roofing material for prefabricated roof panels, standing seam or batten sheet metal roofing provides many opportunities to add value and quality to the system. Advantages include aesthetic appeal, superior weather resistance, increased snow slippage, and durability. For use with building panels, metal is a durable material that can withstand the perils of shipping and handling. It is ideally suited for the conditions encountered at the panel-to-panel and other joints (figure A.2). Typically, seamed metal roofing is quite expensive. Site labor is a major factor in driving up this cost. This is exactly the type of product that can benefit most from a shift into a factory setting.

The finished metal sheet would be fastened to the exterior panel face. The continuous backing of the OSB face would enable the use of a thinner gauge metal than is

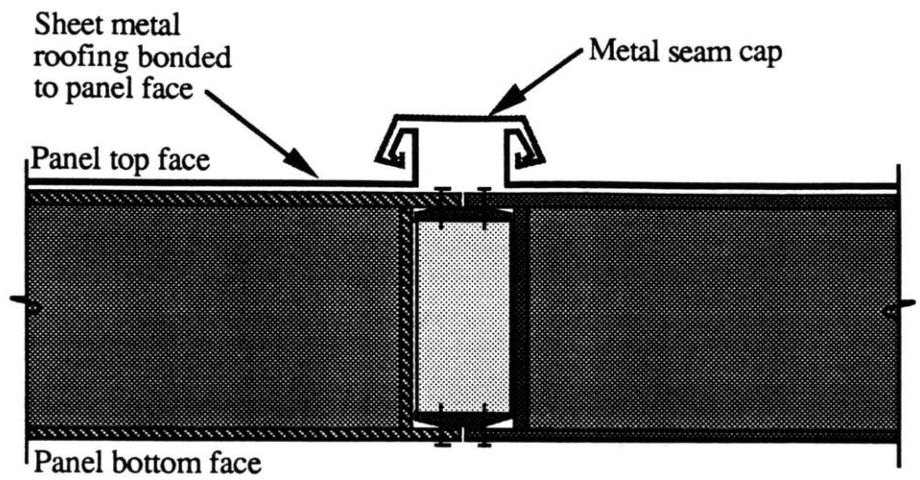


Figure A.2 : Seamed metal roofing on roof panels at panel-to-panel joint

commonly used in this type of roofing. The metal sheet at the edges of the roof panel would be formed based on the joint condition. Most joints could be adapted from the proven technology of seamed metal roofs. This consists mainly of fastened down cleats and snap on seam covers. The cleats would be unnecessary since the metal faces would be attached directly to the panel face. The common seam-to-seam width in metal roofs is 18 to 24 inches. This can be adjusted to the panel dimension.

Seamed metal roofing is a highly desirable roofing that is often unattainable to most homeowners due to cost. To combine this with a roof system that may negate this cost disadvantage while improving the roof panel system itself, is an ideal match.

A.1.3 Dormer component

The gable, or even shed, dormer is the most expensive part of the roof to build on the site (figure 3.2). The dormer component concept calls for the prefabrication of the dormer into a three dimensional stresskin panel, either with ribs or polymer foam injected between two molded faces. This concept is in keeping with the componentized roof system

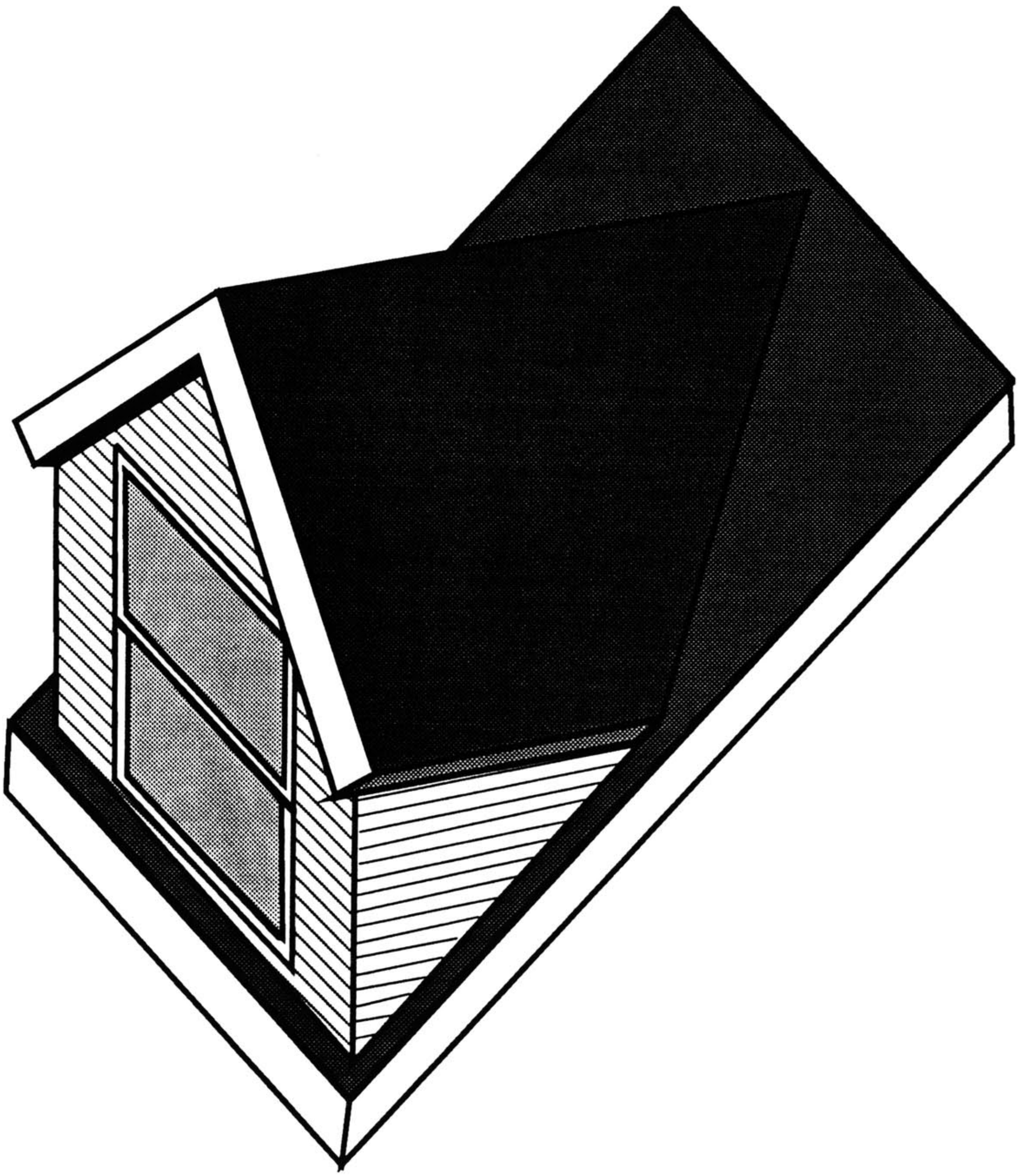


Figure A.3 : Dormer component

and even takes it a step further. It combines one of the most complex framing, roofing and finishing jobs in the house into a prefabricated part (figure A.3).

Dormers are generally built in a few basic widths and are usually small enough to transport and lift into place whole. This concept is not unlike the bay windows prefabricated by window manufacturers for installation in walls.

A.2 Alternative designs

The alternative design concepts presented here are some of the 'dead' or ignored branches of the decision tree described in chapter 4.

A.2.1 Triangle roof panel system

The triangle system is an example of a standard roof panel system. It is based upon the hypothesis that it is much cheaper to produce standard panels than to customize panels per customer orders, and that fewer standard parts are better. Therefore, the goal in developing this concept is to have a minimum family of standard panels that can be combined into the maximum variety of residential roof forms with no customization necessary in manufacturing process, or at the site

The basic premise of the system is that when a roof has hips, turn gables, etc. the roof planes are divided up into a group of triangles. So why not take advantage of that fact ,and fashion panels that easily conform to the final roof shape?

The system is based upon a right triangle whose angles are such that when joined in a hip formation, the desired roof slope results. All parts of the system are derived from the main triangle. They consist of similar triangles whose base lengths are 1/2 or 1/4 of the main triangle (figure A.4). The smaller triangles can form dormers or other smaller elements and will fit modularly into the larger system.

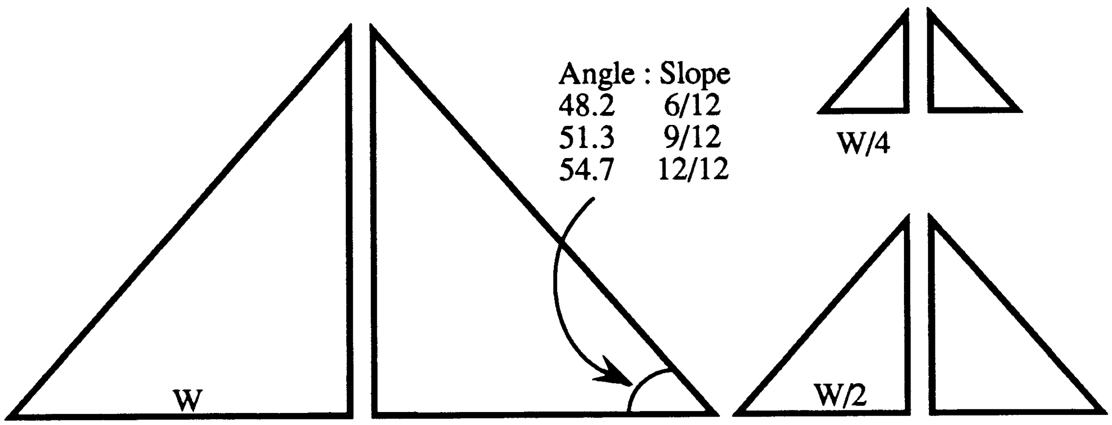


Figure A.4 : Triangle panel system components

Each set therefore consists of six parts (three shapes plus their mirror images). There may be one set each for a number of slopes (say 6/12, 9/12, 12/12). There may also be a few base lengths yielding a few main gable widths (say 24', 28', 32'). This yields 6 x 3 x 3 = 54 panels in the system. Smaller widths could be formed with the smaller triangles. This system may work best as part of an complete building system because of the restrictions imposed on the house dimensions by the triangle base widths.

This system does not take into consideration the possibility that the panel edges would have to be different for panels ending in different joint situations. The joining system would have to accommodate panels at the eave, ridge, panel-to-panel, etc. joints without affecting the panel's primary manufacturing. Perhaps the joint conditions would have to be customized or site built.

This concept imposes severe restrictions on house design, including:

- One slope per building.
- Fixed slope and gable width choices.

• Restricted positioning of roof openings and dormers.

For what part of the housing market may the triangle system be appropriate? For economy housing, a simple gable is most likely acceptable. The hips, dormers & turn gables available in the triangle system may not be necessary for economy housing and are too restrictive for most custom housing. Is there a middle ground where the triangle system, affording some flexibility at standard prices, is appropriate?

A.2.2 Roof panels parallel to ridge line

Level 8 of the decision tree in chapter 4 dealt with the structural strategy for the roof panel system. This section focuses on one of the alternative schemes to the ridge beam, that of 'girder trusses/bearing walls'. This scheme would rotate the panels 90 degrees in plane so that the long dimension of the panel is parallel to the ridge line. The panels would be supported at their ends on girder trusses or bearing walls (figure A.5).

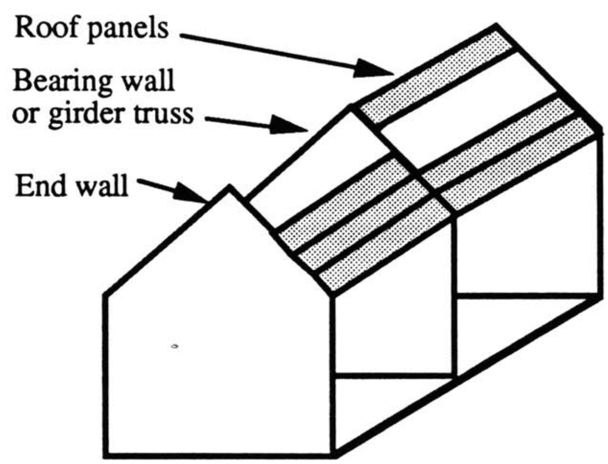


Figure A.5 : Roof panels parallel to ridge line

This scheme seemed attractive for a number of reasons. It restructured the set of joint conditions in a way that was thought to make the whole joint problem simpler (especially for pre-roofed panels). For example, the panel-to-panel joint runs horizontally, allowing for the possibility of overlapping joints (similar to clapboards or shingles) for which gravity would aid in alignment and compression. No ridge beam or collar ties would be necessary in this system. The panels would be supported at their ends by bearing walls or girder trusses.

There are many disadvantages when one considers the architecture design goals set for the roof system. Bearing walls and girder trusses imply cost, plan, and roof cavity space usage constraints. Also, it is hard to imagine this system dealing with design complications such as hips, turn gables, etc. without many beams becoming involved. For these reasons, this scheme was abandoned in favor of eave-to-ridge spanning panels.

This scheme retains promise for row houses, however. In this specialized application (which departs from single family detached), bearing walls exist in the form of party walls and roofs are generally less complex.

APPENDIX B Joint concept tables

Following are illustrations of some of the joint concepts considered in the panel system design along with a table containing some of their pros and cons. The pro and con tables of these joint concepts were derived from the Pugh design sessions in which they were considered.

B.1 Panel-to-panel joint

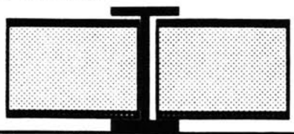
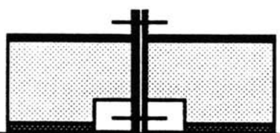
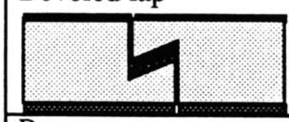
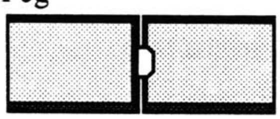
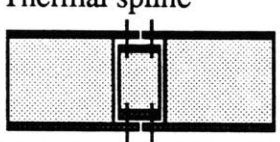
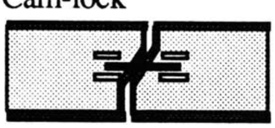
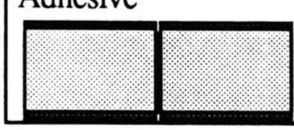
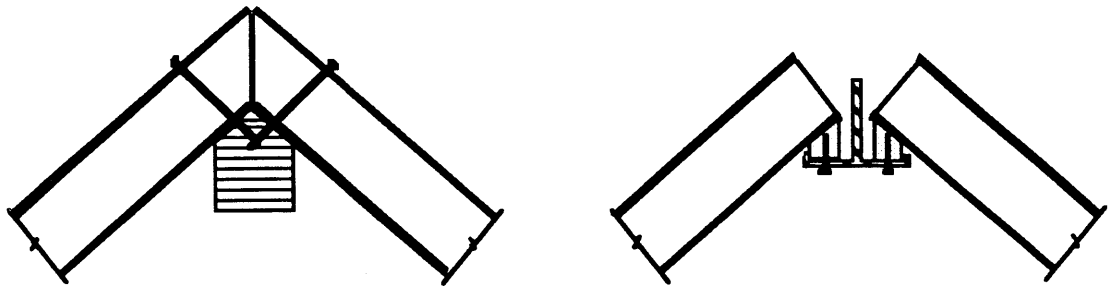
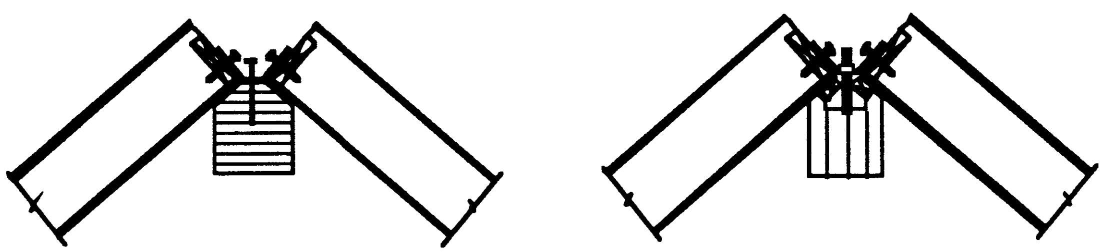
	Pro	Con
I-section 	•symmetrical •covers tolerance errors •panel edged undisturbed	•material uncertain: probably expensive •much thermal bridging •aesthetics: seam exposed •assembly order important
Double lap 	•good weather seal •few steps •few parts •little skill required	•asymmetrical •fragile edges •can't insert panel in between two others
Bolt 	•symmetrical •good seal if top is capped •can do drop-in insertion	•thermal bridging •interferes with roofing surf. •no field tolerance allowed •must patch holes in ceiling •tough to line up bolt holes
Beveled lap 	•self-aligning •low skill requirements •few parts	•fastening method uncertain •assembly order important •damageable outcropping •offset faces confuse module
Peg 	•low skill requirements •few steps •simple concept	•poor sealing opportunities •slide-in assembly •tight manuf. tolerance to match pegs with holes •must align in field
Thermal spline 	•symmetrical •flexible assembly •known & proven tech. •thermally good •good sealing	•multiple parts and fasteners •spline tolerances must be tight •interferes with roofing surface
Cam-lock 	•does not disturb roofing •potential to squeeze good seal and alignment •durable in shipping •easy 1-step process	•cam fastener is expensive •tough alignment of cam arm & hook along joint •must integrate into panel •tight manuf tolerances
Adhesive 	•symmetrical •does not disturb panel edges •can do drop-in assembly	•not robust: affected by weather, sawdust, etc. •no field tolerance allowed •glue may degrade

Figure B.1 : Panel-to-panel joint concepts

B.2 Ridge joint

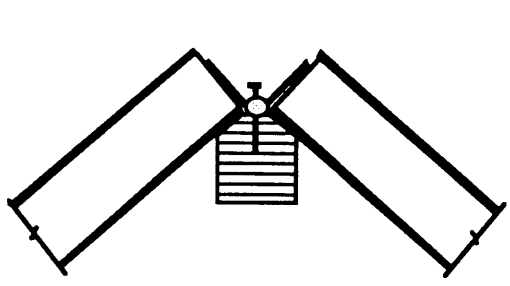


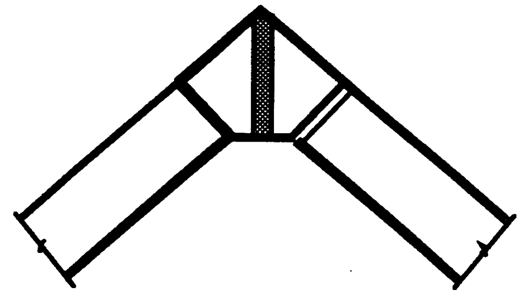
Pro	•simple •known technology	•hook good for assembly ease •good sealing opportunities at hook •beam is small and out of the way
Con	•spikes interfere with roofing •requires expensive timberframe beam •poor with non-foam-core panel	•steel is expensive •how to tie steel into wood structure •steel has poor fire performance



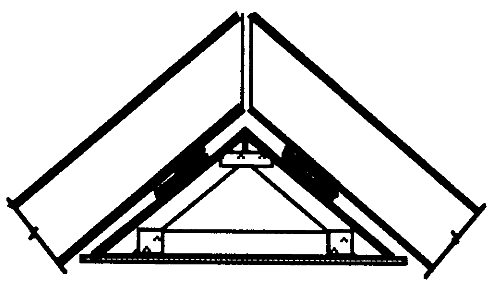
Pro	•all operations easily accessed	•all operations easily accessed •hook good for assembly ease
Con	•fussy •poor sealing opportunities •metal angle may corrode, thermal bridge	•very fussy - many parts •metal angle may corrode, thermal bridge

Figure B.2 : Ridge joint concepts





Pro	•universal for all pitches •few operations	•beam hidden •panel edges not special
Con	•special, complex crane rig needed •hinge expensive •poor sealing opportunities •metal hinge may corrode thermal bridge	•uncertain fastening •assembly problems: no bearing for •panel



Pro	•hook good for assembly ease •roofing not interfered with •easily finished inside •space in beam usable for services •tolerances between hook & ridge •controllable
Con	•poor with shallow pitch •large ridge component to ship & install

Figure B.2 : Ridge joint concepts, continued

B.3 Valley joint

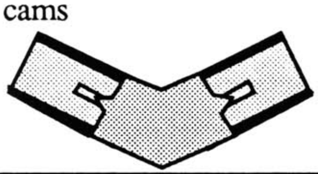
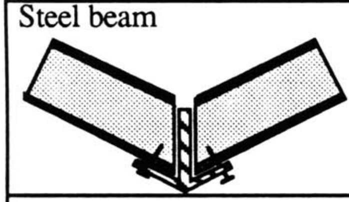
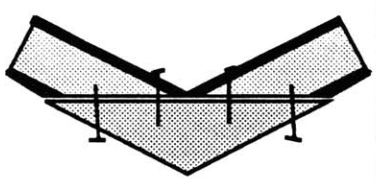
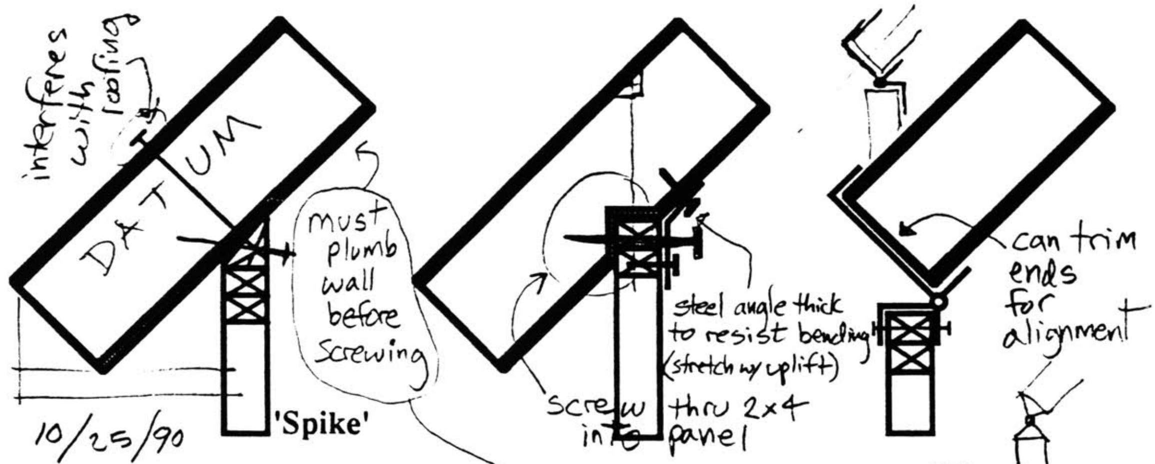
	Pro	Con
Wood beam 	•beam is good for assembly ease	•discontinuous plates provide poor sealing opportunities •odd shaped beam •must finish over steel plates
	•few, lightweight parts •inexpensive materials	•discontinuous plates provide poor sealing opportunities •temporary support needed •must finish over steel plates
Separate valley piece with cams 	•good sealing opportunities •self aligning •easily finished interior and exterior	•tight construction tolerances •complex, expensive part •interface with other joints •no bearing points make assembly difficult
Steel beam 	•beam is simple and good for assembly ease •good sealing opportunities •self aligning	•steel is costly •must finish over steel beam •potentially heave beam
	•no extra parts •no additional dimension	•fastening unreliable •temporary support needed •not durable
	•no extra dimension •large beam aids in assembly	•fastening unreliable •large beam costly •beam a poor structural shape •very fragile edges •seams will show through on interior

Figure B.3 : Valley joint concepts

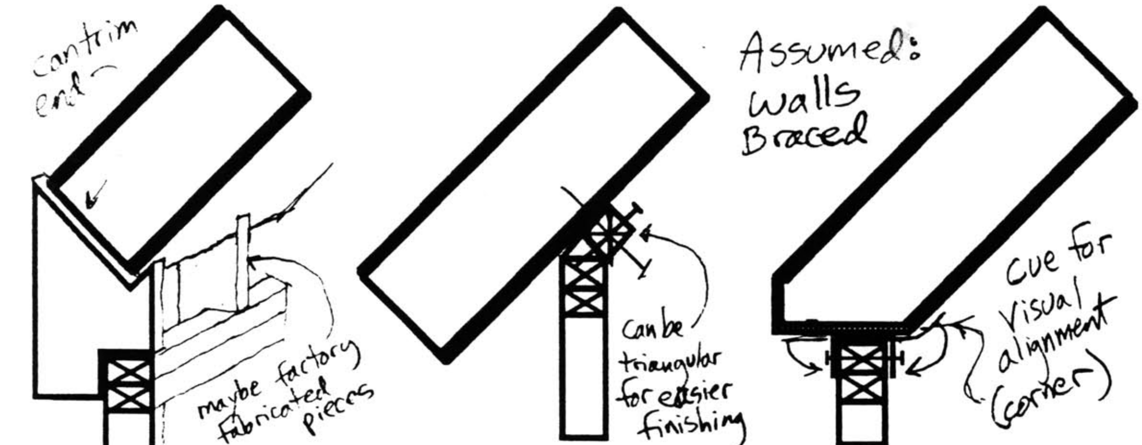
APPENDIX C Eave matrix sheet

Figure C.1 : Eave matrix sheet - following 2 pages



Installed performance	'Birdsmouth'	'Hinge'
Weather seal (water/wind)	+	—
Infiltration seal (air/vapor)	O	—
Thermal bridging	+	—
Fire performance	O	—
Sound transmission	+	—
Aesthetics	O	—
Effect on interior finish		
Durability - Seal	O	—
*- Structure important to evaluate structure	+	+
Allows expansion movement	O	+
Reparability of damage	O	can remove pin → O
Additional features (installed)		
Constructability		
Ease of alignment	+	+
Flexibility of alignment	O	must come straight down (can't swing) → —
Doesn't require high site tolerances	—	Trimmable, but still worse than datum → —
~~Adjustable during assembly~~		
~~Flexible sequence of installation~~ (Ease N/A)	O	O
Special skills of training required		
Assembly steps (time)	+	—
Loose parts	O	—
Ease to trim, finish, roof ← Break up	O	—
Installation climate independent	O	O
Interface with other joints	(with p-2-p) —	O
Field modification ability (correct for tol. error)	—	—
Succeptibility to damage	O	O
Field repairable	O	(can replace) —
Special tools needed	O	O
Special equipment needed		

group



'Frame'	'Ledger'	'Flat-bottom'
–	+	O
–	+	O
if insulated → +	O	O
–	–	O
intermitant contact with roof structure. Insul. good but can fall out → +	O	thru crack → ● –
O	–	O
–	O	flexing of strap up = glue not flexible → O
–	+	● –
But not without disrupting eave/trim, soffit → O	O	O
+	O	O
		Tough to bend sheet metal accurately (moves wall) ?
+	++	–
not from left → –	–	O
–	–	–
O	O	O
–	no wall plumbing needed → +	Bending –
—	O	O
+	interferes ('O'-if triang. piece) –	O
O	O	O
O	(with hip) –	O
–	–	–
O	(even worse if ledger is triangular) → –	O
–	O	metal piece – ●
if field made (miter) → –	O	special bending tool –

APPENDIX D Example of a panel shop drawing

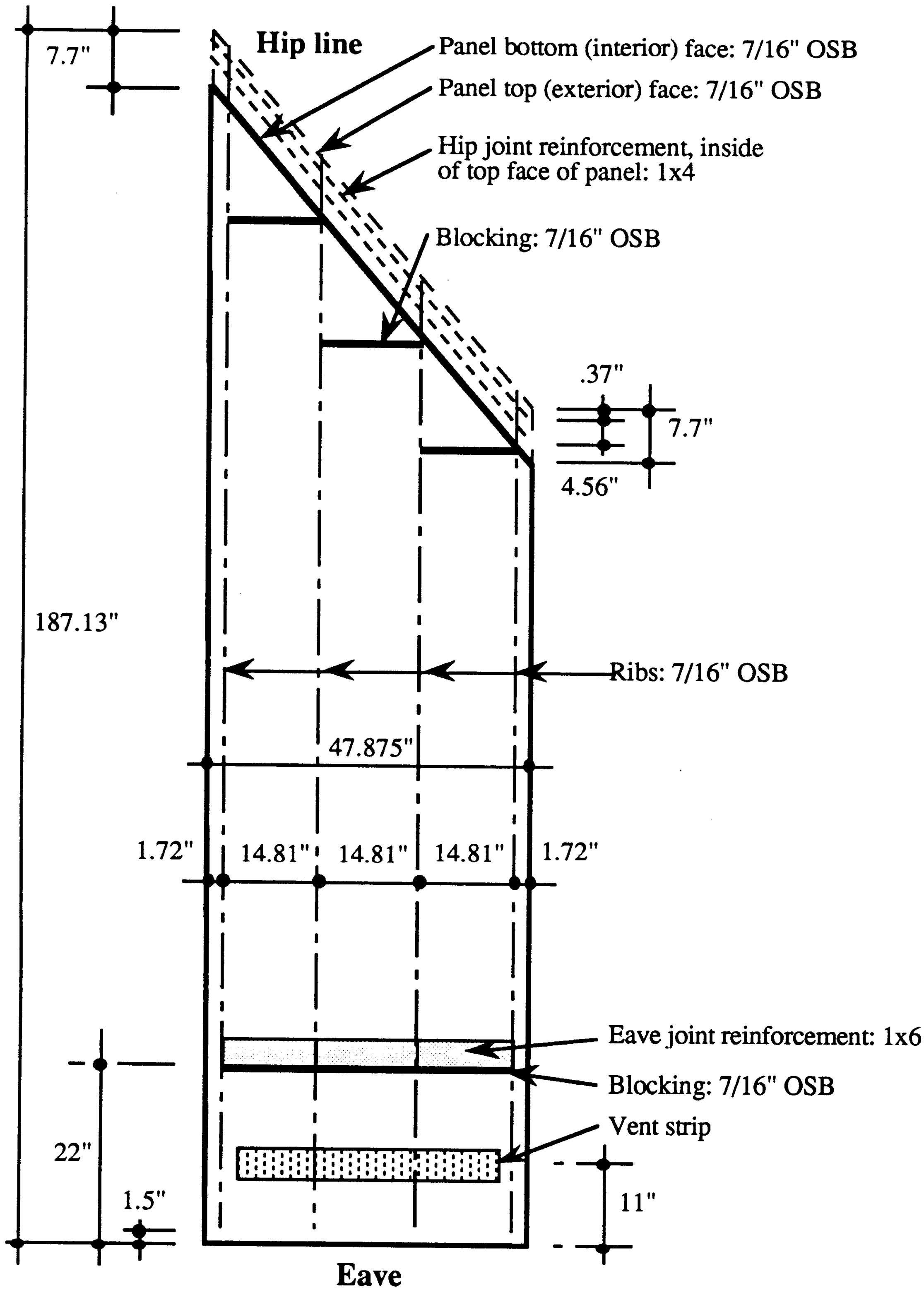


Figure D.1 : Panel shop drawing example, from the hip end of the POC.

APPENDIX E Roof panel ventilation analysis

A rough estimate of the effect of the rib notch design on the airflow within the panel can be made. Ideally, the resistance (total pressure drop) across the passages through the ribs should be insignificant compared to that of the ridge vent itself. The ridge vent is a product whose design has been determined through years of application and study, and therefore, it should control the ventilation airflow rate through the roof panel system.

We will consider the hip end of the POC structure, which is the worst case roof geometry for ventilation. We assume that the length of the ridge vent effectively used by the hip end of the house is equal to L/10 where L is the width of the house. The ridge vent available to vent the entire hip end is therefore 28/10 = 2.8 linear feet or 34 inches. It is 1.5 inches wide resulting in 34" x 1.5" = 51 square inches of opening. Equal amounts of the ridge vent area are appropriated for each linear foot of eave vent. This is a rough approximation since on the triangular panels on the hip end, varying points on the eave vent correspond to different roof areas. There are 43 inter-rib spaces in the hip yielding 51/43 = 1.2 square inches of ridge vent per inter-rib space. The average pathway through from the eave to the ridge vent through the hip passes through 5 ribs. In the POC structure, the portion of each rib hole above the insulation is approximately 4 square inches.

Below is the equation for pressure drop for flow through an orifice. It is used here to compare the proportion of total pressure drop that occurs through the panel ribs to that which occurs across the ridge vent:

$$Q = AC\sqrt{\frac{2\Delta P}{\rho}} \qquad \text{or} \qquad \Delta P = \left(\frac{\rho Q^2}{2C^2}\right)\frac{1}{A^2}$$

Where Q is volume flow rate; A is cross sectional area of the orifice; P is pressure; ρ is density of air; C is approximated to 1 for both cases.

All else being equal for the two cases of the panel ribs and the ridge vent:

$$\Delta P_{holes} = 5_{holes} \times \frac{1}{A^2_{holes}} = 5 \times \frac{1}{4^2} = .31$$

$$\Delta P_{vent} = 1_{vent} \times \frac{1}{A^2_{vent}} = 1 \times \frac{1}{1.2^2} = .7$$

The rib openings account for approximately 1/3 of the total resistance.

A second analysis was undergone to account for the spacing of the holes. This analysis considers the inter-rib spaces as a series of chambers of increasing size connected by an increasing number of orifices (the rib holes). Additional air may enter each chamber through the eave vent. The last, and largest, of the chambers is also open to the ridge vent at the other end. The airflow across each rib consists of flow from its chamber plus all previous chambers. Each chamber contributes an equal amount of flow from its eave vent, as in the first analysis. The air volume from each chamber is proportional to its surface area (and thereby its volume). The total flow from the last chamber must then pass out of the ridge vent. From this analysis, the total resistance (pressure drop) across the 10 ribs is 74% of the total resistance and the resistance across the ridge vent is 26%.

According to both these analyses, the resistances are of the same order of magnitude for the rib openings and the ridge vent for the worst case roof geometry. Therefore, the size and spacing of the rib openings cannot be ignored in designing two-way venting roof panels, and a more detailed analysis is warranted. In addition to the 12" on center hole spacing, a portion of the POC structure roof will be constructed with a 24" spacing. This issue will then be investigated with a smoke test.

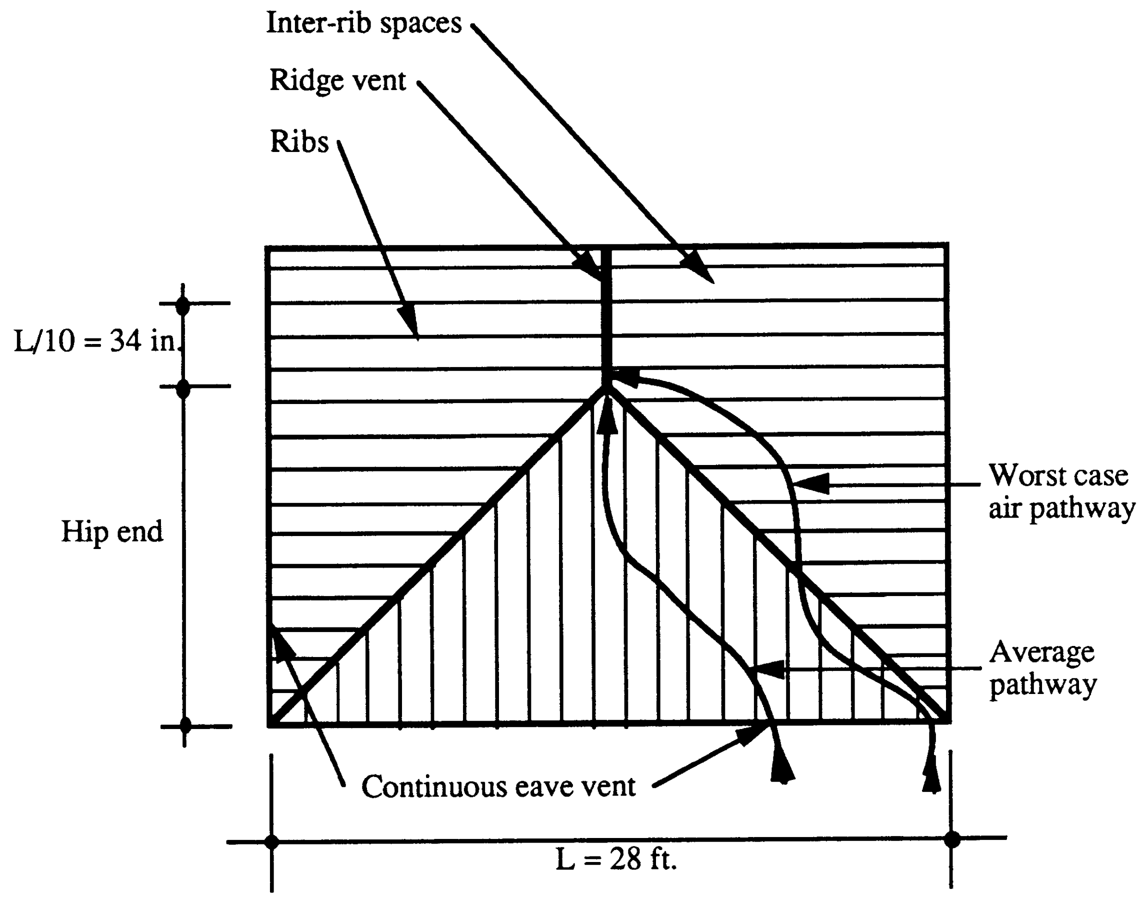


Figure E.1 : Hip ventilation diagram

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Company product literature from:

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Alcoa Building Products Division, Sidney, OH
Astraline Roofing Systems, Lodi, NJ
Atlas Industries, Ayer, MA
Branch River, Smithfield, RI
Cheney Building Systems, New Berlin, WI
Cheney Flashing Co.
Fashion Architectural Roofing, Lenexa, KA
Fischer Cranes, Delphi, IN
Georgia Pacific, Ocala, FL
GE Plastics, Pittsfield, MA
Hiab Cranes, New Castle, DE
Kason Industries, Atlanta, GA
National Crane Co.
New England Homes, Greenland, NH
R-Control Structural Building Panel, Smithfield, RI
Stinger Cranes, Olatha, KA
3M Industrial Specialties Division, St. Paul, MN
Truss Joist Corporation, Boise, ID
Winter Panel, Brattleboro, VT

Communication with:

Acorn Structures, East Acton, MA
Alcan, Kingston, Ontario, Canada
Atlas Industries, Ayer, MA
DOW Chemical, Midland, MI
GAF, Wayne, NJ
GE Plastics, Pittsfield, MA
Home Run Shipping Company, Xenia, OH
Kason Industries, Atlanta, GA
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