The True Cost of SIPs

A Comprehensive Tool for Comparing the Price of Residential Structural Insulated Panel and Stick Frame Construction

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Abstract

Increasing the quality of a home generally increases the cost of construction; however, Structural Insulated Panels (SIPs) illustrate one innovation that may be able to break this rule. Can a small-scale home that is stronger and more energy efficient be built in less time and with less construction waste for the same lifespan cost as traditional stick-frame construction? Small scale residential construction does not benefit from an economy of scale that helps reduce the cost of SIPs in larger homes, this study assesses whether cost-based design decisions can offset the monetary savings from this economy of scale. This study determines the cost per material square foot for nine building elements common to residential construction by incorporating the point in time price of six major category costs. These building element costs are then compiled into a usable, design-based comparative cost matrix tool that allows architects and contractors to assess whether a small scale home design can be constructed with SIPs at the same cost as a typical stick frame structure. Three example homes priced with the matrix conclude that the cost to frame a small scale residential houses with SIPs is approximately 10% greater than stick framing. This additional cost means that SIP manufacturers need to decrease the material cost of Structural Insulated Panels if they are to be comparable in cost to typical stick frame construction for small scale residential homes.

Housing Need

The cost of housing has been steadily increasing across the entire United States while the median gross income has not been rising at a similar rate (Tables 1, 2) and represents the single largest expense to most households (Kaufman 1997). The average home is unaffordable to a significant portion of the population (Kaufman 1997, Williamson 2011). Beyond even the considerable cost of housing, the quality and functionality of the structure is also a concern (Kaufman 1997). Increasing the quality of a home generally increases the cost of construction; however, technology and innovations in alternative construction methods have begun to break this rule (Gagnon and Adams 1999). Structural Insulated Panel (SIP) construction illustrates one such innovation; that a stronger, better insulated, and more energy efficient home can be built in less time and with less construction waste for the same cost after five years of operation (Daly 2008, Weber 2003). Thus, SIPs may be an answer to increasing the amount of quality housing, while at the same time not increasing the economic burden that housing represents.

Table 1: The Adjusted 2015 Cost of a Home Compared to Gross Per Capita Income in the U.S. (2010 U.S. Census, Davis and Heathcote 2007)

Year	Median Gross Income	Median Cost of Home	Land Value	Structure Value	Cost of Home / Income Ratio
1980	$27,000	$127,300	28.9%	$90,500	4.7
1990	$33,500	$137,800	36.2%	$87,900	4.1
2000	$40,200	$163,000	34.6%	$106,600	4.1
2010	$43,700	$221,800	26.1%	$163,900	5.1

Table 2: The Adjusted (2015) Cost of a Home Compared to Gross Per Capita Income in Colorado (2010 U.S. Census, US Department of Commerce Bureau of Economic Analysis, Davis and Heathcote 2007)

Year	Median Gross Income	Median Cost of Home	Land Value	Structure Value	Cost of Home / Income Ratio
1980	$28,900	$173,000	50.8%	$85,100	6.0
1990	$33,800	$144,100	43.7%	$81,100	4.3
2000	$44,200	$227,100	58.9%	$93,300	5.1
2010	$46,100	$254,300	43.4%	$144,000	5.5

Davis and Heathcote in 2007 (Table 2) found that the cost of land in Colorado is significantly higher than the United States average while the median value of the structure is lower than the national average. This means that the cost of building with SIPs as a percentage of the overall home value is decreased in the state of Colorado due to the additional cost of the land (Davis and Heathcote 2007).

The cost of typical construction is undercut by an enormous economy of scale; the majority of construction in the United States is wooden stick-frame construction (Gagnon and Adams 1999). SIP construction, on the other hand, has a market share of only about 1%, of which residential construction represents 70% of the industry’s total production (Gagnon and Adams 1999). SIPs have a significantly larger material cost—partly since they do not benefit from a worldwide economy of scale which drives down cost for stick framing—but mostly due to their high cost of manufacturing. Their initial upfront cost is greater than that of traditional stick frame housing by about 3-20% (Daly, 2008). However, SIPs do realize a certain economy of scale that offsets their material cost on a project basis; homes over roughly 1000 square feet are more likely to be comparable in cost to a stick frame structure when several years of energy savings are factored into the cost of the home (Thomas et al. 2005). This number (1000 square feet) is dependant on many factors such as the complexity of the structure, the experience of the construction crew, the remoteness of the project, the amount of energy saved, and additional factors such as the general shape of the building. I propose that through proper design based on the analysis of the associated costs, emphasizing aspects where SIP panels are as economical as traditional stick framing, high-quality, small-scale SIP homes under 1000 square feet can be built at a comparable cost to typical methods.

This study on Structural Insulated Panel construction will attempt to circumvent the economy of scale associated with conventional construction and assess whether a SIP house can be economical in spite of increased material expenses. The solution lies in the quantitative comparison between the two methods and what design decisions need to be considered when attempting to negate the additional upfront cost of SIP construction. This study builds a cost comparison matrix that develops a framework for making an estimation of expenses associated with SIP and stick frame construction which can then be adjusted to suit the needs of an individual project. This will provide designers with a quick method to make and assess design decisions for new SIP construction and keep it economically comparable to stick frame structures. Finally, this study utilizes the cost comparison matrix by assessing three typical types of single family residential homes of approximately 1000 square feet, the saltbox, the bungalow, and modern. These residential designs will be utilized to judge the effectiveness of the matrix as well as provide a representation of some of the building elements commonly used in different home types.

Stick Frame Construction

The majority of single-family homes, accounting for 55% of new-builds in the United States, are light-frame wood, or *stick frame,* construction (Mullens 2008). These structures utilize individual pieces of dimensional lumber assembled onsite, a skilled-labor intensive process (Mullens and Arif 2006). Following the erection of the frame (See Figure 1), the entire structure must be insulated with fiberglass batt insulation or foam insulation, sheathed with plywood or oriented strandboard (OSB), and finally wrapped in a moisture barrier.

The cost of stick frame construction originates largely from two separate markets, labor and the lumber industry (Mead 1966). Construction labor is relatively inexpensive: the median gross income for a laborer in 2013 was 30% lower than the national median gross income for all professions (Bureau of Labor Statistics). The other market influencing the cost of construction is the lumber industry, which has an oligopsonistic structure (many sellers and few buyers) at the raw material level (timber, i.e. harvested trees) and an almost perfectly competitive model at the product level (dimensional lumber) that responds elastically to market demand (Mead 1966). The oligopsonistic structure of the timber industry results from Canadian forest resources being held publicly or privately in the hands of a few major firms; this allows the few buyers to dictate the price of timber and the market reveals both implicit and explicit collusion (Mead 1966). The elastic lumber market does not represent the economy of scale within the construction industry; the competitive nature of the firms is derived from the quantity of separate enterprises. However, each firm realizes an effective economy of scale due to the huge amount of lumber produced and the large supply needed by the construction industry (Mead 1966). The net effect of these two forces is to drive the price of timber down while the cost of lumber responds to market supply and demand, theoretically maximizing benefits to the overall market (Mead 1966).

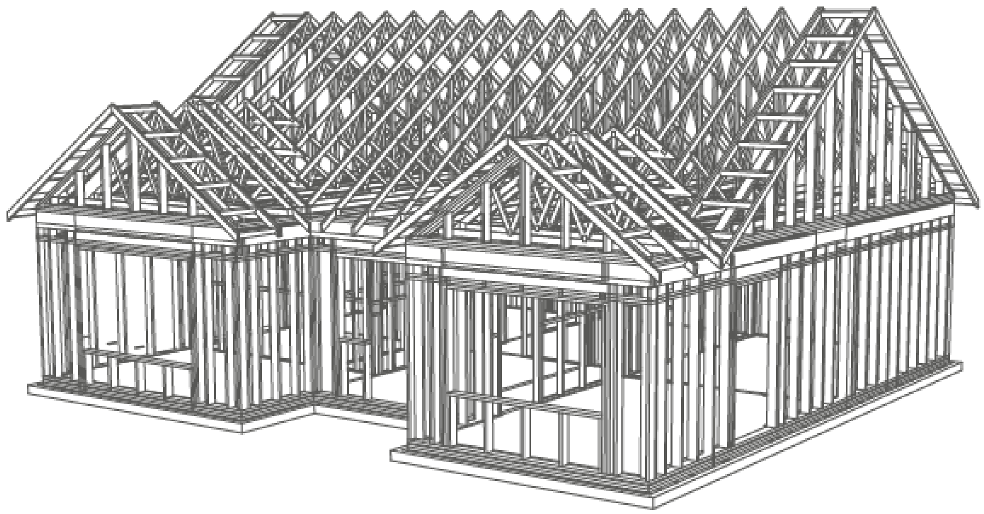


Figure 1 (Author 2014, heavily edited from CTS Design 2012)

Structural Insulated Panels (SIPs)

Structural Insulated Panels (SIPs) are a method of prefabricated construction that combines the structural support of a building, the insulation, exterior and interior sheathing, and an air-barrier into a single factory-produced unit (Kermani 2006, Yang et al. 2012) (See Figure 2). SIPs are an example of a relatively new building technology that has the ability to compete with stick frame construction (Daly 2008). SIPs have managed to capture only approximately 0.5-1% of the current housing market, largely due to technological concerns, market unfamiliarity, a lack of industry marketing, and a higher material cost (Gagnon and Adams 1999, Mullens 2008). In the late 1990's the Structural Insulated Panel Association (SIPA) pursued an aggressive marketing plan, largely targeting the construction trades and related professionals (Gagnon and Adams 1999). This marketing strategy has helped SIPs to obtain a 50% market share increase from 2000-2005, offering a promising commitment to continued growth (Mullens and Arif 2006). Additionally, following the economic downturn of 2008, SIP manufacturers saw a 53% smaller decrease in overall productivity (-4% for SIPs as compared to -8.5%) than conventional construction industries (Seward 2012).

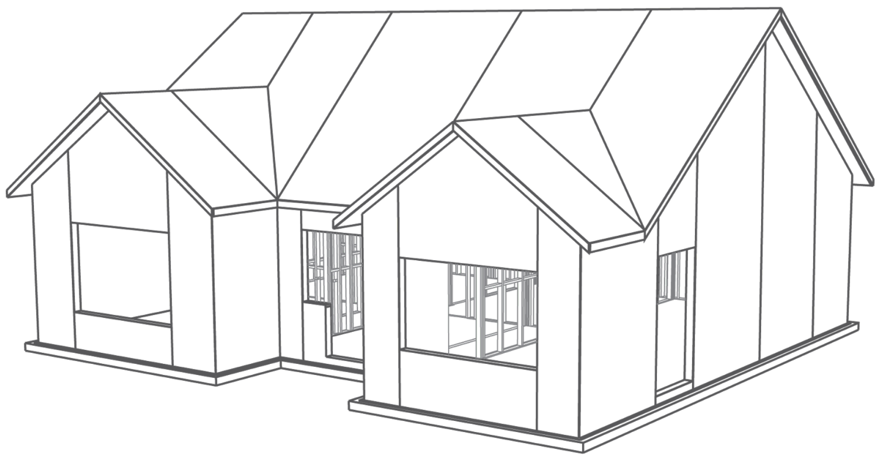


Figure 2 (Author 2014, heavily edited from CTS Design 2012)

SIPs are categorized as *sandwich panels,* meaning that they are fabricated by laminating two stronger materials on either side of a layer of lower density material (the core); this separates the high strength materials and greatly increases the flexible rigidity of the composite form while reducing material mass (He and Hu 2008, Yang et al. 2012). They adhere to the concept of the *stressed skin principle* when properly fused together; the stress expressed on either outside skin acts as a tension counter for the panel as a single unit. When the panel attempts to deflect one skin needs to compress and the other stretch, the amount of stress applied to each skin is proportional to the distance between the two skins. In other words, a greater distance between the skins creates a stronger panel. Strength is generally optimized with a panel thickness of 8¼" for axial (vertical) loads and 10¼" to 12¼" for transverse (horizontal) spanning loads (Premier SIPs Load Charts). This creates a dimensionally-stable and rigid structural panel (Cathcart 1998). Figure 3 represents the typical composition of a SIP with an OSB skin and expanded polystyrene forming the core.

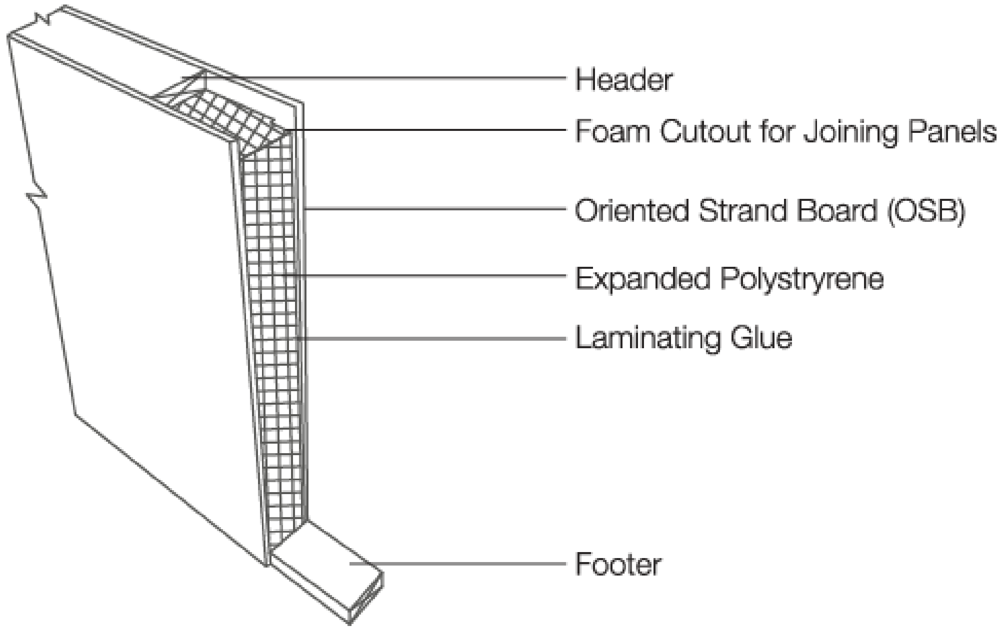


Figure 3 (Author 2014, edited from Gunstock Timber Frames, 2009)

History of SIPs

The principals behind Structural Insulated Panels were first conceived in the 1930's by the Forest Products Laboratory (FPL) as a method for conserving forest resources; the FPL tested sandwich panels comprised of a honeycomb-paper core between two plywood skins for a structural application. These early investigations led to the construction of a small home built with the honeycomb panel system; the structure was used by the University of Wisconsin-Madison for 60 years before being demolished (Gagnon and Adams 1999). In the 1950's SIP technology was refined to its current composition; an interior core of rigid, structural foam surrounded by two thin skins. Several trial homes were constructed during this time but the industry failed to ignite due to a lack of demand (Gagnon and Adams 1999). Twenty years later, in the 1970's, the industry started to take off by promoting its products as an alternative to stick framing (Seward 2012).

SIP Materials Overview

Structural Insulated Panels can be created from a wide variety of materials and two separate methods, provided they adhere to the basic composition of a SIP outlined above. Skins are where SIPs have the most flexibility in material choice; common materials include cement board (CSIPs), oriented strandboard (OSB) or plywood, orthotropic thermoplastic laminate (plastic sheets that have directional strength), glass fiber reinforced polymer (GFRP) sheets, and steel sheet metal (Jing and Raongjant 2013, Kermani 2006, Vaidya et al. 2010, Mussa and Udden 2010). Each material offers its own advantages and drawbacks. Cement board is much more flame retardant, but heavier and more difficult to work with than wood; it also does not offer the convenience of attaching finishing materials associated with wood (Kermani 2006, Technical Bulletin 2: Fire, Jing and Raongjant 2013). OSB and plywood are similar in function and utility; the difference is that OSB is more commonly used due to its availability in much larger sheets (up to 8'x24') and lower cost (Kermani 2006, Mullens and Arif 2008). OSB-skinned SIPs offer lightweight construction, can achieve a 30 minute fire barrier with a single layer of ½" gypsum, and offer easy workability and finishing attachment (Seward 2012). Both sides are clad completely in wood meaning that special fasteners for finishing materials are not required. However, they are susceptible to water damage and must be properly sealed (Emery 1986). Orthotropic thermoplastic laminate (CSIPs) and glass fiber reinforced polymer (GFRP) are plastic composite sheets; they offer decreased fuel for fires (but possess a low melting point), lightweight construction, thinness, and a high strength-to-weight product (Jing and Raongjant 2013, Kawasaki and Kawia 2006). Steel sheet metal offers higher fire resistance and a high strength-to-weight ratio, but are more cost prohibitive and harder to manipulate in the field (Quin et al. 2007).

There are several options for the plastic foam core but all are similar structurally. Expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane (PUR) foams are the three most commonly used, and all function in the same manner (Kermani 2006). All three resist water due to their closed cell structure, are petroleum-based products, and have similar structural integrity (Kermani 2006). All three rigid foams also have dimensional stability, this means that they are more likely to keep their shape over the life of the structure (Mullens and Arif 2006). Polyurethane has the best insulating capabilities and structural strength but is also the most expensive, while extruded polystyrene falls in the middle and expanded polystyrene has the lowest cost, strength, and insulating value (Simon et al 2013). Graphite can serve as an additive to EPS to increase its insulative properties (BASF 2008).

Two methods exist for adhering the foam core to the skin: laminating with a structural grade glue (BASF 2008) or forming and curing the foam mixture between the two outer skin panels (Kermani 2006). Lamination is more commonly used for its cost effectiveness and superior durability—in compression tests the foam itself fails before the glue (Yang et al 2012). Adhesives are either two component adhesives—which are stronger and have better adhesion qualities but require accurate mixing ratios—or only have a single component (BASF 2008).

The panel comes in a variety of widths to coordinate with the widths of dimensional lumber for ease of assembly. Four inch (4½”) and six inch (6½”) widths are common for walls; while eight inch (8¼”), ten inch (10¼”), and twelve inch (12¼”) widths are generally utilized for roofs where additional insulation and spanning capabilities are required (Seward 2012). Dimensional lumber fits *inside* the OSB sides; meaning the width of the foam for a four inch panel is exactly 3½” thick and the overall width is 4½” thick. This simplifies the construction process of the structure and allows for some in-field modification while also increasing the structural integrity of the building (Mullens and Arif 2006).

The typical SIP is comprised of a rigid expanded polystyrene foam core skinned with 7/16” OSB on both sides and laminated with structural grade polyurethane plastic-wood adhesive (BASF 2008, Kermani 2006). EPS is the most common core material—it is used in 85% of SIPs—since it is readily available and inexpensive (What are SIPs 2011). OSB is similarly inexpensive and available in large sizes, up to 8’ x 24’ which allows it to span longer distances (Kermani 2006).

Environmental Concerns and BioSIPs

There are several environmental and health impact concerns with Structural Insulated Panels, namely carcinogenic chemicals, petroleum usage, and end of lifecycle waste. Styrene and benzene-bases are both organic gaseous chemical compounds that can be produced by expanded polystyrene (Hawley-Fedder 1994). Styrene is present in very low quantities, typically 1% for food grade EPS, as the monomer that is chemically combined to form the polymer polystyrene. Styrene may have carcinogenic and toxic properties, though it is also naturally present is some fruits, cheeses and wines (Cohen et al. 2002). Cohen et al. (2002) concluded that polystyrene used for food packaging did not result in adverse health effects. In SIP construction the polystyrene is sealed within the building’s walls and only has human contact during construction. Benzene-based hydrocarbons can be produced during incineration of polystyrene during low-temperature incineration, such as in a house fire (Hawley-Fedder 1994). Benzene is a carcinogen according to the US Department of Health and Human Services and is categorized as a worldwide health concern due to its presence in petroleum fuels. The use of petroleum to make polystyrene is a concern as a use of a non-renewable resource; however, EPS is only 2% petroleum by volume and has a lifecycle expectancy in SIPs of 50-100 years.

Formaldehyde is present in OSB and continues to offgas throughout its lifespan (Emery 1986). *Voluntary Product Standard PS 2* dictates the level of formaldehyde emissions present in plywood as 0.20 ppm and is generally accepted as the national standard for OSB. Emery (1986) found levels to be half this amount at 0.1 ppm in a large scale test chamber. However, formaldehyde is a carcinogen and a national health concern due to its prevalence in manufactured products that have direct contact with humans. OSB emits more formaldehyde under damp or damaged conditions and thus should not be subjected to moisture—since moisture destroys the structural integrity of SIPs they are protected against this during the construction process and this concern is largely negligible (Emery 1986).

Recycling waste or used polystyrene is mostly hindered not by the inability to recycled but by the lack of collected material to recycle; transporting expanded polystyrene to recycle is typically regarded as ineffective due to the low ratio of material to volume—it is composed of only 2% material (Seward 2012). Incineration as an option but only in extremely high heat incinerators, to eliminate residual chemicals EPS needs to be burned at a temperature above 1000℃ (producing only carbon dioxide, water vapor, and heat) while the majority of industrial incinerators in the United States only burn material at 850℃ (Hawley-Fedder 1994).

BioSIPs are a potential remedy for the adverse environmental and health impacts of SIPs. BioSIPs utilize a Engineered Molded Fiber (EMF) skin and a soy-derived foam insulation (Herdt and Schauermann 2012). The EMF skin is comprised of “waste” fiber material—such as recycled paper, wood and forest waste, and construction and industry wood residues (BioSIPs Corporate Overview 2015). This is molded into cellular panels from a pulp-slurry (Herdt and Schauermann 2012). The soy foam insulation—which does not have any chlorofluorocarbons or formaldehyde— is then sandwiched between two EMF panels to form the complete BioSIP (Hardy). BioSIPs perform to SIP structural standards (Herdt and Schauermann 2012) and soy foam insulation performs as well as polyurethane spray foam insulation (Hardy). However, Green Building Advisors notes that all soy foam spray insulations contain petroleum and that the US Department of Agriculture has ruled that a spray foam need only be 7% renewable-based to be labeled as a bio-based foam (Spray Foam Insulation: Open and Closed Cell 2014). Thus, BioSIPs may be an alternative to the environmental concerns of typical Structural Insulated Panels.

SIP Construction Method

There are several methods for joining SIPs together, they are all based on the idea of mechanically fastening the the two pieces of OSB to an additional piece of lumber. It is important to note that the SIPs are not directly fastened to one another; this would be unstable and would not form a flat finished surface. OSB splines, dimensional lumber, wooden I-joists, or pre-installed metal “clamping” fasteners—called Cam-lock panel joint connections—are utilized to assemble a complete wall (R-Control SIPs: Structural Insulated Panels Construction Manual 2012, Simon et al. 2013). These are fastened together with normal wood screws or extra long SIP fastening screws where needed (e.g. at corners or connecting the roof to the walls). A continuous bead of silicone or rubber solvent caulking is added both between panels and between the panels and any dimensional lumber (Do-All-Ply® Sealant 2004). Finally, a weather and air-tight tape is applied to the seams between panels. Roofs and floors use the same method except that OSB splines do not support a transverse load, thus dimensional lumber and wooden I-joists replace them (R-Control SIPs: Structural Insulated Panels Construction Manual 2012).

Windows and doors are framed in a very similar manner as described above, dimensional lumber is always used to provide support the the edge of windows and doors. Only a single “stud” is required around both windows and doors (R-Control SIPs: Structural Insulated Panels Construction Manual 2012). Window headers can be either of two options, a header made out of a SIP (for short spans) or a typical header built with dimensional lumber (for spans larger than 8’). SIP headers prevent thermal bridging and so are preferable when possible (R-Control SIPs: Structural Insulated Panels Construction Manual 2012).

SIPs are fastened to the foundation in a similar manner to typical stick-frame construction. However, the OSB should always be protected from moisture—it should not be placed directly on any foundation. Rather, a piece of pressure-treated lumber should form the sill plate while the bottom plate (attached to the top of the sill) can be comprised of either pressure-treated or untreated lumber. The OSB should then fully rest on this treated plate and not overhang since it is providing the support of the structure (R-Control SIPs: Structural Insulated Panels Construction Manual 2012).

Structural Insulated Panels can be solely utilized to provide the bearing capacity of a roof provided the span is not too long—the maximum span of twenty feet is achieved with a 10¼” SIP with double dimensional lumber splines spaced every four feet or a 12¼” SIP with a single I-joist spaced every four feet (Premier SIP Load Charts). The panels will either meet at the peak and be fastened together or they will be fastened to a ridge beam. If roof spans longer than twenty feet are needed SIPs can be applied on top of a truss system, in which case they only provide the structure necessary to span the distance between the trusses (R-Control SIPs: Structural Insulated Panels Construction Manual 2012). See Appendix A: Construction Methods for an abridged detailed construction manual taken from R-Control SIPs: Structural Insulated Panels Construction Manual 2012.

SIP Performance and Advantages

Structural Insulated Panels, as with all building materials, have their benefits and their shortcomings (See Table 3 for a summary). However, SIPs offer a variety of benefits over conventional stick frame construction. Construction time is typically significantly reduced with a SIP home (Murtaza et al. 1993, Gagnon and Adams 1999, Mullens and Arif 2006). The process of construction is more controllable and precise through the use of factory-produced pieces which helps reduce construction time (Mullens and Arif 2006, Wright 2011). While some aspects of the construction process were shown to take additional time when utilizing SIPs—such as unloading and panel placement—these additional labors were more than offset with other time savings (Mullens and Arif 2006). The majority of the time saved while employing unskilled labor was shown to be with complex roof construction (Mullens and Arif 2006). Mullens and Arif showed a 50% decrease in on-site construction time between a similar SIP home and a stick frame construction. Other studies also reveal that SIPs have an approximately 50% decrease in onsite construction time (Drain et al. 2006, Murtaza et al. 1993). However, increased time is necessary for shop labor, meaning the factory's labor spent in assembling the panels, before construction begins. The SIP manufacturer must also assess the wall and roof construction to verify that in-field assembly is build to SIP code specifications (Murtaza et al. 1993). Shop labor spent off site at the factory accounts for an extra 20% increase in labor hours; however, even with the additional shop and design labor overall time spent is reduced by 30% (Murtaza et al. 1993).

Table 3: SIP Performance

SIP vs Stick Frame Performance Category	**% Change**
Construction Time Savings	+50%
Strength	+20-30%
Energy Savings	+18-24%
Onsite Waste Savings	+30-98%
Additional Shop Labor	+20%
Factory Waste	+10-20%
Design Time	+0%

The energy used in producing building materials accounts for 25-40% of the total energy consumed within modern countries and conventional construction accounts for 40% of the waste in landfills (Ramirez et al. 2012). Structural Insulated Panels virtually eliminate onsite waste due to framing, up to a 98% decrease (Seward 2012). This does not include factory waste; however, that can be minimized and potentially recycled (Xiaoyong Pan et al. 2012).

In a typical residential home 12% of the panels is lost in the factory due to waste (Mullens and Arif 2008). Surplus pieces are kept and reused when possible, the polystyrene foam commonly utilized is recyclable, and the OSB used in manufacturing comes from fast-growing and underused tree sources such as young spruce and pine (Xiaoyong Pan et al. 2012, Seward 2012, European Panel Association). Not only is the polystyrene foam recyclable, it also is only 2% petroleum based plastic by volume; the remaining 98% is insulating air captured between the cells (Seward 2012).

Energy use throughout the life cycle of the building is greatly reduced compared to stick frame construction due to the superior insulating abilities and airtightness of SIP construction

(Mullens and Arif 2008). Blower tests have shown SIP construction to be 5 times more airtight than traditional stick frame buildings; this is a significant amount since buildings lose 40% of their heat from air infiltration (Seward 2012). Airtightness is related to soundproofing; SIP homes were rated by occupants to be considerably quieter than stick frame (Qian et al. 2007). However, some residents have reported echoing to be an issue in SIP homes (SIP Homeowner 2014). Thermal bridging is virtually eliminated compared to approximately 10-15% of the surface area in conventional construction that promotes heat loss (McCullom and Krarti 2010). This, as well as non-standard insulation installation in stick frame homes, can result in a whole wall R-value loss of 15-30% from the rated value (McCullom and Krarti 2010). SIPs avoid these issues by having continuous and standardized rigid insulation. Heating energy savings were measured by McCullom and Krarti (2010) to be from 18% and 24% for a home in Denver, Colorado for a 4½" and 6½" SIP respectively. The placement of insulation in the roofs of SIP homes, at the cathedral of the roof in lieu of the flat ceiling area, accounts for an additional 22-40% energy savings if ductwork is run through the ceiling (Thomas et al. 2005).

SIPs have been tested for a variety of structural load conditions including shear forces, double shear, creep over time, compressive strength, bending, tension, and delamination. SIPs responded exceptionally well to shear and double shear forces, and no delamination and negiable deformation occurred under sustained applied loads (Kermani 2006, Meng and Raongjant 2013). Creep under sustained loads was also negligible and the material recovered fully after the load was removed (Kermani 2006). Bending, compressive, and tensile strength were tested to adhere to building regulations; in all respects SIPs exceeded standards (Yang et al. 2012, Yeh et al. 2008). Delamination was shown to be the failure method of SIPs under high stress applications; however, OSB skinned panels tend to delaminate at a much higher force (Mussa and Uddin 2010, Mussa and Uddin 2011). All SIPs met building code standards for delamination under high stress conditions as well as over time (Yeh et al. 2008). SIPs performed well under flexibility tests; the inherent flex within the system is considered the factor behind their seismic durability and SIP structures have been reported to withstand magnitude 7.2 earthquakes (Mussa and Uddin 2011, Yeh et al. 2008). They outperformed conventional structures in hurricane conditions for total damage and projectile penetration, except OSB-skinned SIPs which performed poorly at a high velocity blunt-object impact (Yeh et al. 2008, Vaidya et al. 2008, Vaidya et al. 2010)

Drawbacks

Structural Insulated Panels have many qualities that positively affect their performance; however, they still have not made a significant impact on the housing market due in part to their disadvantages (Gagnon and Adams 1999). Cost continues to be the primary prohibitive factor affecting widespread SIP utilization and a wide range of additional cost estimates are given within the SIP industry. These range from 2%-20% more than stick frame construction (Gagnon and Adams 1999, Wright 2011, Seward 2012, Christian et al. 2006).

Another factor that could impact the potential benefits of SIP construction is the experience of the construction crew. This has the potential to change the time savings associated with SIPs: an inexperienced crew can lengthen the total construction time (Seward 2012). However, an inexperienced crew can also still have a faster construction time than a stick frame home built by an experienced crew; especially if labor is abundant (Mullens and Arif 2006). A crew experienced with SIP building can erect a structure in a considerably shorter time and construction companies have reported that they enjoy working with SIPs far more than typical stick framing (Wright 2011)

The air tightness of SIP homes can result in a lower air quality in the finished home if it is not provided sufficient air exchange (Seward 2012). However, air quality can be controlled through the installation of an air exchange system, this is simple and inexpensive to do and improves overall air quality (Seward 2012).

Structural Insulated Panels are affected by a variety of environmental concerns. Mold and mildew is a common issue, particularly in high humidity locations. Insects can burrow into the foam and decrease its insulating properties by creating large, difficult-to-fix air pockets (Seward 2012). Both of these issues can be fixed with additives to the panel system: a mold coating prevents growth and SIPs can be treated with boric acid to repel insects (BASF 2008).

Water damage and fire resistance are also significant concerns (Seward 2012, Technical Bulletin 2: Fire). Assembled SIP seams are sealed on the outside with a bituminous-based chauk while the inside seams are waterproofed with a moisture resistant tape (BASF 2008). Fire resistance is typically achieved through installation of ½” gypsum board, one layer will provide the structure with a 30-minute fire rating while a double layer can provide up to a 1-hour fire rating where necessary (Technical Bulletin 2: Fire). The foam can also be treated with HBCD (Hexabromocyclododecane) to increase fire resistance (Wright 2011). Expanded polystyrene begins to soften at 212˚F and will eventually melt (it does not possess a true melting point) at higher temperatures which means that it is a material relatively ineffective in a fire (Fire Performance & Safety 2010).

Thus, mold and insect concerns are both as easy to treat in SIP construction as in stick frame. SIP structures are more susceptible to water damage than stick frame, but through proper sealing this can be negated. Gypsum is utilized in both types of construction for fire resistance; however, SIPs do require twice the amount of gypsum to achieve a comparable fire rating (Technical Bulletin 2: Fire).

SIP Economic Factors

There are a wide variety of costs and savings that change relative to conventional construction when utilizing Structural Insulated Panels (Murtaza et al. 1993). The costs assessed within this study (hereinafter referred to as *Category Costs*) are: Materials, Equipment, Schedule and Construction Loans Savings, Transportation, Energy Savings, and Direct Labor (Murtaza et al. 1993, Drain et al. 2006). All of these factors affect the final cost of a SIP structure (Laquatra et al. 1990).

Many companies (R-Control SIPs, Premier SIPs, SIP Home Systems) claim a 0% cost increase after energy savings over a period of five years. This calculation depends on thermal performance of the structure, labor costs, its location, and the current cost of energy as well as the cost of materials (McCullom and Krarti 2010). The initial increase in construction cost varies widely between sources and locations; from 2-10% (Gagnon and Adams 1999), 5-15% (Wright 2011), and up to 20% (Seward 2012, Christian et al. 2006). Other studies have found a cost savings of up to 10% in non-residential applications when schedule, labor, and energy savings are considered (Murtaza et al. 1993).

Materials

There is a significant difference between the cost of materials for SIPs and dimensional lumber—which benefits from having a much lower material production cost as well as a majority share of the housing construction market (Mullens 2008). This helps to result in a lower cost for dimensional lumber and its long-standing production means that the overall industry and individual mills are already well established (Cathcart 1998). Beyond the infrastructure the demand is also stable (Mead 1966). SIPs can be as much as 20% more costly than dimensional lumber and insulation for the same size structure (Seward 2012, Christian et al. 2006). The raw materials: foam, OSB, and glue, used in SIP production accounts for almost half of the cost of production with the remainder going to labor costs—shop labor—and factory overhead, including equipment and software (Gagnon and Adams 1999). The material cost for SIPs composes the majority of the overall cost.

Cost of Design/Engineering

Murtaza et al. in 1993 claimed that there was an additional design cost of almost 10% associated with SIP construction. This was due to the requirement that all aspects of the structure be intensely planned out before the panels could be manufactured. Developments since then in BIM software have negated this cost in residential construction since the building is designed the same using either method of construction (Kieran and Timberlake 2008). The only additional design cost that would typically be associated with SIP construction in recent years is the architects' need to familiarize themselves with the panel system (Daly 2008). The cost of laying out, cutting, and the method of assembling the panels is included in the cost of the material for SIPs.

Equipment

Additional equipment is needed at the construction site to account for the larger size and weight of the building panels (Mullens and Arif 2006, Drain et al. 2006). A crane to assemble the panels is required onsite to ensure proper safety; however, the time necessary to assemble the structure is drastically reduced by utilizing a crane (Mullens and Arif 2006, Drain et al. 2006). The monetary savings from this reduction in labor is greater than the expense of hiring a crane (Mullens and Arif 2006).

Schedule Savings and Construction Loans

The total time to construct a SIP home is generally significantly reduced; this can result in a considerable savings for the owner (Murtaza et al. 1993). While this has a much higher percentage of savings for a business or industry, it still makes an impact on the total cost of residential construction (Mullens and Arif 2006). The ability to inhabit the new home more quickly can potentially result in rent savings for the owner (Mullens and Arif 2006). Moving in more quickly also results in paying the significantly higher interest on construction loans (than mortgage rates) for a shorter amount of time (Christian et al. 2006). This study will only look at the savings for construction loans over the amount of time saved from framing (not including electrical or finishing labor-time saved).

Transportation

SIPs are assembled in large pieces off site and then must be transported to the site. The truck to move these large pieces as well as their unloading and organization result in a substantial time investment—generally a full day for a large home—and the additional costs associated with this (Mullens and Arif 2006). Murtaza et al. (1993) estimated that in SIP construction the total cost of transportation is 20% higher than conventional construction by needing to ship the large pieces. Complex panels, such as curves, add to the shipping cost (Drain et al. 2006). The additional cost of transportation largely results from the potential efficiency of the framing crew who would otherwise purchase and transport materials in stick frame construction. An inefficient crew would be more costly in terms of labor hours to purchase the materials as well as the construction company's upcharge.

Energy Savings

SIPs are significantly more energy efficient than conventional homes (McCullom and Krarti, 2010). The energy cost savings can offset the additional cost of the SIP panels over time (Christian et al. 2006; Daly, 2008). McCullom and Krarti (2010) reported a 18-24% heating energy savings in SIP homes verses stick frame in Denver, Colorado. McCullom and Krarti's (2010) study assumed that the whole wall R-value of SIPs were equal to that of a stick frame wall with fiberglass insulation and that the SIP building only saved energy through a reduction in air infiltration. An EPS 4½" SIP wall has a realized whole wall R-value of 13.1 while XPS and PUR insulations increase this value to 17.7 and 22.7 respectively (Whole Building Design Guide: Structural Insulated Panels 2013). Oak Ridge National Laboratory gives the effective whole wall R-value of a 2x4 stud wall to be 10.0 for R-13 rated insulation and 13.3 for a 2x6 wall with R-19 insulation (Kosny 2004). Another opportunity is to completely or partially negate the cost of energy through the use of supplementary energy generation such as solar panels (Christian et al. 2006). This study assumes that the whole wall R-value for SIPs is the same as for stick frame construction and that air infiltration is the only aspect that is affecting energy savings by using a 4½" SIP wall and a 2x6 stud wall insulated with R-19 fiberglass insulation (R-values of 13.1 compared to 13.3). Additional savings from potentially reducing the size of the HVAC system is also not accounted for.

Shop and Direct Labor

Labor in SIP construction shifts the location and level of efficiency as well as replacing a large amount of human labor with machine and computer labor. The amount of off-site labor (shop labor) increases in SIP construction by approximately 20% while onsite labor decreases 50% (Murtaza et al. 1993, Drain et al. 2006). This results in a significant overall labor cost savings; approximately 15-30% for residential projects with an inexperienced crew (Drain et al. 2006, Mullens and Arif 2006). Shop labor is built into the cost of material—this is part of why SIP material is more than twice as expensive as stick frame material—and is not assessed in this study for that reason.

Methods

Structural Insulated Panels (SIPs) and typical stick-frame construction can have a significant cost difference due to their separate cash flow patterns (Murtaza et al. 1993). See Table 4 for an overview of these patterns over time (with time progressing from left to right), SIPs have a much larger initial investment that slowly pays off over many years. The methods used in this study seek to compensate for the different patterns to develop a tool for assessing the costs associated with individual building components commonly used in typical residential construction. However, this study is a framework for cost comparison and is not a substitute for a detailed cost analysis (a bid) performed on an individual project basis.

Table 4 | Cash Flow Patterns Over Time

	Material	Equipment	Framing Labor	Electrical	Finishing	Loans	Energy	Resale Value
SIPs	+++	+	-	-	-	-	-	+
Stick	-	-	+	+	+	+	+	-

The cost of construction is an ever-changing variable and individual to each construction project. Historically, pricing a building has taken the form of looking at similar examples, the cost of labor, the location, type of home, and quality of construction (Craftsman 2014 National Building Cost Manual 2013). Once a general value is ascertained a bidder can start to derive a more accurate cost of construction based on the design, labor costs, company overhead, profit margins, and material cost. This study seeks to quantify the first of these two steps; a more accurate number would require a bid from both a construction company as well as a SIP manufacturer. However, many construction companies are hesitant to offer a solid bid on SIP buildings if they have only worked with typical stick frame construction (Wright 2011).

There is always a *degree of use* associated with any modularised project (Murtaza et al. 1993), this study will assume 100% use of SIP construction for the envelope—including the roof, floor, and walls—versus 100% stick frame construction to account for individual building elements. SIP construction is used to replace the building envelope; it will be compared to the stick frame construction costs of erecting the frame of a structure, equivalent assembled wall insulation abilities, and exterior and interior sheathing.

Costs will be constrained to the Front Range of Colorado, the central portion of the state including the cities of Denver, Boulder, and Fort Collins/Loveland, to control for cost variations between localities. This area has a higher cost of construction compared to both the national average and the state average. Colorado is approximately 1% more expensive while the front range is 5% more costly than the national average (Craftsman 2014 National Building Cost Manual 2013). This increase applies to both SIP and stick frame construction but it should be noted that cost may be higher or lower in different localities.

The architecture of this study will assess two aspects of the costs associated with SIP construction; Category Costs and Building Element Costs. Both categories need to be considered if this study is to be able to determine the comparative costs associated with design decisions. Every Building Element Cost will have each Category Cost built in to the pricing to create an information-based cost-analysis design guide. Each aspect was compared to stick frame construction techniques by Material Square Footage—or envelope surface area—of the cost of the exterior envelope. Interior walls, partitions, and porches are not considered since stick framing would typically be used for those applications. See Table 5 for a flowchart describing the overall procedure for estimating the economic analysis. Steps 1-4 are given in the comparative cost matrix while steps 5-6 are simple calculations required by the designer based on the building that is to be assessed.

Table 5 | Procedural Flowchart

1	Define Major Categories
2	Define Building Elements
3	Find Category Costs (by Material Square Footage)
4	Find Building Element Costs (by Material Square Footage)
5	Find Building Element Weights (% of Total Construction by MSF)
6	Sum Total Costs/Savings

Building construction categories were utilized to define the total costs associated with a specific Building Element beyond just the cost of materials. The major categories that were assessed were Materials, Cost of Design/Engineering, Equipment, Schedule Savings and Construction Loans, Transportation, Energy Savings, and Shop and Direct Labor (see Table 7).

Building Elements are defined to specify a broad range of typical construction features utilized within residential construction. Those assessed within this study include Simple Pitched Roof, Complex Pitched Roof, Flat Roof, Roof Overhangs, Apertures, Straight Wall, Short Span Floor (<12'), Long Span Floor (12'-20'), and Dormer Windows. This list is does not include all building elements, but rather gives a designer the ability to consider common forms in small scale residential construction.

Category and Building Element Cost information is drawn from one of these four sources: secondary literature, manufacturer pricing, case studies, bids, or a combination from these sources. Each source was used where the information is available. Secondary literature includes pricing information based on available case study reviews as well as pricing handbooks and articles from RSMeans, an independent construction pricing organization that is regarded as the standard for cost estimation in construction. Manufacturer pricing was based on SIP project bids from a manufacture in the Front Range Area, Grand County SIPs; it was used to assess material costs. Three case studies were assessed to ensure consistency between cost data, each is a SIP home of roughly 1000 square feet. Larger homes have different Category Costs and thus data from homes larger than 1500 square feet was not utilized. For each category the cost was calculated as the price per Material Square Footage, for flat rate estimates (such as transportation) this was divided by 3150—the assumed MSF of a 1000 square foot home—to divide this cost amongst the entire building by MSF to allow comparison with stick frame construction. Table 6 provides an example of how a Category Cost is estimated.

Table 6 | SIP Material Category Cost Example

Building Element	**Square Feet of Material**	**Cost per Square Foot**	**Total Cost**	**Adjusted Cost per Square Foot**
Roof (Pitched, Simple)	1,920	$4.48	$8,610.00	$7.05
Walls	1,984	$3.63	$7,200.30	$6.20
Cutting	3904	$1.17	$4,581.39	-
Accessories + Additional Lumber	3904	$0.87	$3,413.38	-
Soft Costs	3904	$0.53	$2059.87	-

Building Element costs were defined through a process of calculating the total cost of each individual Category Cost as it pertains to that element. Some Category Costs, such as Equipment, is equal across all Building Elements while others are particular to that element. Table 7 shows an example of how a Building Element is calculated. Category Costs were estimated for both SIP and stick frame construction, totaled for each type, and finally the stick frame total cost per MSF was subtracted from the SIP total cost per MSF to discern the difference between the two construction methods.

Table 7 | Building Element Example

Category Costs	**SIP ($/sq ft)**	**Stick Frame ($/sq ft)**	**Additional Cost of SIP Construction**
Materials	$6.45	$2.26	$4.19
Equipment	$0.33	$0.00	$0.33
Schedule Savings Construction Loans	-$0.08	$0.00	-$0.08
Transportation Unloading	$0.16	$0.23	-$0.07
Five Year Energy Cost	$0.85	$1.00	-$0.15
Direct Labor	$1.02	$2.64	-$1.62
Total	**$8.73**	**$6.13**	**$2.60**

Finally, a cost comparison taking into account the total additional cost of each Building Element was developed to compare the difference between small scale SIP and stick frame construction. The cost of the Building Elements can be considered to be consistent between projects (to make this cost analysis readily usable for design purposes) while the surface area of Building Elements is individual to that structure. By multiplying the additional cost of the Building Element by the surface area of that element a preliminary comparison can be developed on a project basis. This allows for the design team to exert minimal effort and time to consider the total cost increase or savings by utilizing SIPs for each Building Element (see Table 8 for an example). Further, this method allows for the design team to consider which building elements are contributing to the largest cost differences and make design decisions based on the percent change between stick frame and SIP construction techniques. This is the Comparative Cost Matrix and the tool garnered from this study for future use by design professionals.

Table 8 | Matrix Example

Building Element	**SIP vs Stick ($/ MSF)**	**x Surface Area (MSF)**	**= Cost Difference**
Simple Roof	-$0.30	800	-$240.00
Complex Roof	$0.18		
Flat Roof	$1.99		
Total	**-**	**100%**	**-$240.00**

Category Costs + Definitions

Category Costs were priced by Material Square Footage; they will remain consistent when utilizing the matrix throughout individual building projects. Point-in-time costs (as of 2010 through 2015) were used to develop the expense of each category cost. This study assumes that there was not a significant change in non-cost related variables over the last two decades, i.e. labor is considered to be as efficient now as it was twenty years ago, homes use a similar amount of BTUs to heat a home, etc.

Materials

Sources: Grand County SIPs 2010, Christian 2008, Christian et al 2006

Material costs are the expenses related to the physical elements of the building; the SIPs, fasteners, additional dimensional lumber needed, and sealants (finishing materials).

Materials includes the expense of shop labor. This study priced materials for 4½" SIPs for walls, 8¼" SIPs with double 2x8 splines for the roofs, electrical chases installed, and window and door apertures cut out and lumber included but not framed. SIPs cost will be based on the expense related to one surface square foot of material. For stick frame construction materials comprise the dimensional lumber, insulation, sheathing, fasteners, air-barrier, tax (7.65%), waste (10% typical) and unaccounted-for items (10%). Stick frame materials costs were calculated by the author based on an example clear wall or roof span then divided by the MSF to determine the cost per MSF.

Due to the nature of construction costs primary being determined through a bidding process this study has looked at three sample projects that had a total cost breakdown (a detailed bid) attached. These projects were provided by Grand County SIPs—Precision Building Products. Costs per MSF were determined for each project, then the average compiled to account for differences in the total cost of the material. All square footages are given in Material Square Feet. See Table 9 for an overview of the projects assessed for material cost and Appendix B for design drawings of each project.

Table 9 | SIP and Stick Frame Material Cost Overview

Building	**Source**	**Information Gathered**
Tapscott Cabin	Grand County SIPs	SIP Total Material Cost Per Square Foot
Slockett Cabin	Grand County SIPs	SIP Total Material Cost Per Square Foot
Cedar View	Grand County SIPs	SIP Total Material Cost Per Square Foot
ZEH5	Christian 2008	Donated SIP Material Cost Per Square Foot
ZEH2	Christian et al 2006	Donated SIP Material Cost Per Square Foot
Stick Frame	Home Depot, Menards	Stick Frame Total Material Cost Per Square Foot

Tapscott Cabin, 2010

1,156 square feet, Ground floor + loft

Roof = 8.25” with double 2x8 spline, 4’ wide, 8/12 pitch

Walls = 4.5” door and window cuts, headers, electrical chases, 10’ height, 4’ wide

Table 10 | Tapscott Cabin SIP Material Cost

Building Element	Square Feet of Material	Cost per Square Foot	Total Cost	Adjusted Cost per Square Foot (includes extras)
Roof (Pitched, Simple)	1,920	$4.48	$8,610.00	$7.05
Walls	1,984	$3.63	$7,200.30	$6.20
Cutting*	3,904	$1.17	$4,581.39	-
Accessories + Additional Lumber	3,904	$0.87	$3,413.38	-
Soft Costs**	3,904	$0.53	$2059.87	-

Slockett Cabin, 2010

816 square feet, Ground floor

Roof = 8.25”, 2x8 block spline, 4’ wide, 12/12 pitch

Walls = 4.5” door and window cuts, headers, electrical chases, 8’ height, 4’ wide

Table 11 | Slockett Cabin SIP Material Cost

Building Element	Square Feet of Material	Cost per Square Foot	Total Cost	Adjusted Cost per Square Foot (includes extras)
Roof (Pitched, Simple)	1,472	$4.49	$6,609.28	$7.11
Walls	1,344	$3.61	$4,851.84	$6.23
Cutting*	2,816	$1.35	$3,795.04	-
Accessories + Additional Lumber	2,816	$0.79	$2,228.53	-
Soft Costs**	2,816	$0.48	$1361.16	-

Cedar View, 2010

1444 square feet, Ground floor + loft

Roof = 8.25”, 2x8 block spline, 4’ wide, 12/12 pitch

Walls = 4.5” door and window cuts, headers, electrical chases, 8’ height, 4’ wide

Table 12 | Cedar View Cabin SIP Material Cost

Building Element	Square Feet of Material	Cost per Square Foot	Total Cost	Adjusted Cost per Square Foot (includes extras)
Roof (Pitched, Complex)	2,752	$4.48	$12,328.96	$7.76
Walls	2,944	$3.63	$10,686.72	$6.91
Cutting*	5,696	$1.50	$8,556.22	-
Accessories + Additional Lumber	5,696	$1.16	$6,612.02	-
Soft Costs**	5,696	$0.62	$3527.54	-

*factory creates rough openings for window and doors, angle cuts, gable cuts, etc.

**Tax + Drafting + Engineering Services from SIP manufacturer

Table 13 | Average Adjusted Cost Per Square Foot, 2010

Building Element	Adjusted Cost per Square Foot (includes extras)
Simple Pitched Roof	**$7.08**
Complex Pitched Roof	**$7.76**
Walls	**$6.45**

Department of Energy : Zero Energy Homes

In the mid 2000’s the Department of Energy assessed five projects for their cost of construction in creating a Zero Energy Home (ZEH). These homes were extremely efficient, well constructed structures that provided energy use data for a number of years under normal occupation (Christian 2008, Christian et al. 2006). The following two examples are part of this study, both are experimental homes built with volunteer labor and begin to offer an insight into the potential of SIPs in creating high quality homes. In both projects the SIPs were donated, this may have resulted in a recorded lower expense than the actual retail value that the panels would cost. Design documents were unavailable.

Department of Energy - Building Technology Program : ZEH5

Oak Ridge National Laboratory (Christian 2008)

1232 square feet, Ground floor + concrete poured basement

Roof = 8¼”, 2x8 structural spline, 4’ wide

Walls = 6½” door and window cuts, headers, electrical chases, 8’ height, 4’ wide

Costs = $5.77 / MSF (no differentiation between roof and walls)

Department of Energy - Building Technology Program : ZEH2

American Society of Heating, Refrigerating and Air-Conditioning Engineers

(Christian et al 2006)

1060 square feet, Ground floor

Roof = 6½”, 2x6 structural spline, 4’ wide

Walls = 4½” door and window cuts, headers, electrical chases, 8’ height, 4’ wide

Costs = $6.43 / MSF (no differentiation between roof and walls)

Stick Frame, 2010

Sources: Home Depot, Menards

Single story, 4/12 pitch

Pitched Roof = Trusses, R-30 fiberglass batt insulation

Flat Roof = 2x12 construction, R-30 fiberglass batt insulation

Walls = 2x6 construction, R-19 fiberglass batt insulation

Aperture = same as walls (equals wasted wall)

Dormers = 63% complex roof, 37% wall by MSF composition

House wrap, OSB sheathing, fasteners, waste, unaccounted for items

Stick frame costs were based on a sample section of a building in order to simplify the cost estimation process by assessing each for cost individually. The design of the building element was based on typical stick frame construction and material prices were given according to retail price and did not include construction discounts (materials are typically charged to the owner at retail price and construction discounts are assumed to be profit). Unaccounted-for items is included to estimate for costs not directly priced, such as fasteners, overbuying, connections, equipment depreciation and replacement, and items not included in specific building elements (i.e. a sill plate or a spacer). 10% waste is an industry standard for a contingency at the construction site. See Table 14 for an overview of the material costs associated with stick frame construction and Table 15 for an example of how material costs were estimated for a single building element.

Table 14 | Stick Frame Material Costs

Building Element	Material Square Footage	Total Cost	Cost per MSF
Roof (Pitched, Simple)	924	$4,423.91	$4.79
Roof (Pitched, Complex)	924	$4,616.65	$5.00
Roof (Flat)	896	$2,876.80	$3.21
Roof Overhang	19	$77.45	$4.08
Dormer*	-	-	$4.00
Walls	224	$506.40	$2.26
Aperture	224	$506.40	$2.26
Long Span Floor	448	$2,149.70	$4.80
Short Span Floor	336	$1,351.58	$4.02

*Dormers were assumed to be 63% complex roof, 37% wall by MSF composition

Table 15 | Material Square Footage Cost Estimation Example (Wall)

Number	Items	Cost	Total Cost
23	Vertical Studs	$4.25	$97.75
10	Top + Bottom Plates	$6.65	$66.50
7	Sheets OSB	$12.87	$90.90
4	Insulation (R-19)	$24.96	$99.84
0.5	Housewrap	$64.85	$32.43
10%	Unaccounted-for Items	$38.74	$38.74
10%	Waste	$42.61	$42.61
7.65%	Tax	$35.86	$35.86
Total	**224 MSF**		**$504.63**

Equipment

Sources: Duffy Crane and Hauling

Equipment costs will cover the additional equipment necessary for SIP construction; namely the time necessary utilizing a crane as well as the cost to bring the crane to the site. Stick frame will be used as the baseline and thus will incur an equipment cost of $0.00 since typical construction equipment furnished by the framing crew is utilized in both methods. The total cost of the crane is divided by 3150 (assumed MSF for a 1000 square foot home) to determine the cost per MSF.

Table 16 | Equipment Cost Estimates

Crane Rental	Company	Capacity (tons)	Reach (feet)	Cost Per Hour	Hours Needed	Total Cost	Cost Per Square Foot (TC/ 3150)
Forklift with extended boom	Duffy	4	30’	$130.00	8	$1,040.00	**$0.33**
Hydraulic Truck Crane	Duffy	38 ton	31’ jib 124’ boom	$155.00	8	$1,240.00	$0.39

Schedule Savings and Construction Loans

Sources: Drain et al 2006, Mullens and Arif 2006

RSMeans 133 hours saved with a 4 man crew = one week

Labor Savings (below) 116 with a 3 man crew (for 1000 sq ft home) = one week

Does not include additional savings for quicker construction elsewhere

This category cost will be defined as the savings from less time paying construction loan interest for a shorter amount of time at current market rates. This cost will result in a negative number for SIPs assuming an experienced crew. Construction loans loans are given at a significantly higher interest rate than mortgages, the home builder should also account for the additional cost of not being able to occupy the residence while it is under construction (as would be the case with mortgages). This study does not account for the additional savings of occupying a separate house nor the additional time savings from faster construction elsewhere, such as with installing electrical, cabinets, or interior finishes that result from the precision of SIP construction and entire wall structural surface area.

Assumptions: 12 month loan, SIP construction takes 1 week less time

Date Accessed: March 1st, 2015

Table 17 | Construction Loan Rates 2015

4.600% 20% Equity	Randolf-Brooks Federal Credit Union
5.975%	National Exchange Bank and Trust
5.677%	ENT Ferderal Credit Union

Table 18 | Construction Loan Savings 2015

Loan Amount	**Average Rate**	**Savings Per Week**	**Total Savings Per Material Square Feet (3150)**
$150,000	5.826%	$182.06	$0.06
$200,000	5.826%	$242.75	**$0.08**
$250,000	5.826%	$303.44	$0.10

Transportation

Sources: World Freight Rates, Freight Quote

SIPs require additional transportation costs due to their large size; transportation costs will account for the expense necessary to bring the materials to the site. For small scale residential construction this will assume one truck-load from the SIP factory to the site using typical delivery methods. Stick frame transportation costs are assumed to be 10% of the cost of materials. This is a standard utilized by construction crews to account for gas, wear on vehicles, and other related expenses (Framing Material Estimate 2007).

48' flatbed, no liftgate

1 day, 1 trip, 9 tons

86 pallets @ 96" x 48" x 6"

$35,000 insurance

30 miles from business with forklift to construction site (with crane)

3150 sq ft of material

Table 19 | SIPs Transportation Costs (Cost / MSF)

Company	**Quote**	**Total Cost Per Material Square Feet (3150)**
Flatbed Logistics-FQ	$568.88	$0.20
Freight Quote.com, Inc.	$338.86	$0.12
World Freight Rates.com	$398.32	$0.14
World Freight Rates.com	$440.15	$0.16
Average	$441.05	**$0.16**

Energy Savings

Sources: (McCullom and Krarti 2010)

This cost is a comparison between SIPs and stick frame construction in Denver, CO. Due to SIP's superior performance they use less energy to heat and cool the home. McCullom and Krarti (2010) did not account for the greater whole wall R-value of SIP construction; they only used the difference in air exchange rates between the building methods. They conducted blower door tests for two rooms—one SIP and the other stick frame—to measure the Effective Leakage Area (ELA). The ELA was found to be 4.6 in^2 for the wood-frame room and 0.4 in^2 for the SIP room, this difference in ELA resulted in the simulated energy savings.

McCullom and Krarti (2010) used a eQuest, a program to simulate the energy used in a home. To compensate for this 4½" SIPs with a whole wall R-value of 13.1 ft^2/F/Btu were used while R-19 ft^2/F/Btu fiberglass batt insulation that had a whole-wall R-value of R-13.3 ft^2/F/Btu were utilized in stick frame pricing (Oak Ridge National Laboratory). McCullom and Krarti (2010) assumed insulation to be placed in the ceiling joists; however Thomas et al (2005) showed that placing the insulation in the roof rafters resulted in 5%-25% with R-19 and 22%-40% with R-48 insulation less heat loss through the roof. SIP roofs place the insulation in the roof rafters resulting in additional energy savings not calculated in this study. Energy savings will be compiled for five years as that is the industry standard for energy savings payback time.

Table 20 | SIP and Stick Frame Energy Costs Over Five Years

Building Element	Annual Denver Home Therms Per Square Footage	Therms Per Material Square Footage (3150)	Cost / Therm*	Cost Per Material Square Footage	Five Year Cost Per Material Square Footage
SIP	0.46	0.26	$0.65	$0.17	**$0.85**
Stick Frame	0.56	0.32	$0.65	$0.20	**$1.00**

*Author's Xcel Energy Bill, January 2015

Direct Labor

Sources: (Mullens and Arif 2006; Drain et al. 2006)

Shop labor is defined as the labor costs incurred in the factory while direct labor is the cost from the construction of the building onsite. For SIPs this will be assembling and finishing with a moisture barrier; for stick frame Direct Labor costs will comprise all of the labor costs as there will not be any additional factory labor not included in the price of the materials. The crew will be comprised of two framers and one foreman, the assumed rate for this study is approximately twice the hourly wage of the crew members to account for the overhead costs of the company.

Table 21 | SIP and Stick Frame Labor Hourly Rates (Bureau of Labor Statistics 2013)

Job Description	**Hourly Wage (Mean)**	**Assumed Rate (2x hourly wage)**	**Labor Cost Per Minute**
Residential Construction Laborer	$15.55	$35.00	$0.58
Colorado Construction Laborer	$15.12	$35.00	$0.58
Construction Manager Cost	$44.57	$90.00	$1.50
Total		**$160.00**	**$0.88**

Table 22 | SIPs Labor-Time Costs

Building Element	**RSMeans (Drive et al. 2006)**	**Mullens and Arif 2006**	**Average (mins / sq ft)**	**Labor Cost ($ / MSF) @ $0.88 / min**
Roof (Pitched)	1.74	1.32	1.53	**$1.34**
Walls	1.06	1.25	1.16	**$1.02**
Floor	-	2.15	2.15	**$1.89**
Dormer	3.10	-	3.10	**$2.73**
Overall (other)	1.17	1.76	1.47	**$1.29**

Table 23 | Stick Frame Labor-Time Costs

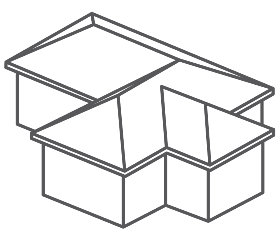
Building Element	**RSMeans (Drive et al. 2006)**	**Mullens and Arif 2006**	**Average (mins / sq ft)**	**Labor Cost ($ / sq ft) @ $0.88 / min**
Roof (Pitched)	4.08	4.36	4.22	**$3.71**
Walls	3.3	2.71	3.01	**$2.64**
Floor	-	-	-	**-**
Dormer	4.15	-		**$3.65**
Overall (other)	3.81	3.54	3.68	**$3.24**

Results

Dormer Windows

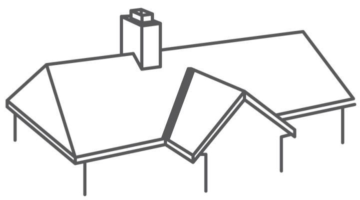
Category Costs	SIP ($/sq ft)	Stick Frame ($/sq ft)	Additional Cost of SIPs
Materials	$6.95	$4.00	$2.95
Equipment	$0.33	$0.00	$0.33
Schedule Savings Construction Loans	-$0.08	$0.00	-$0.08
Transportation Unloading	$0.16	$0.40	-$0.24
Energy Cost	$0.85	$1.00	-$0.15
Direct Labor	$2.73	$3.65	-$0.92
Total	**$10.94**	**$9.05**	**$1.89**

Complex Pitched Roof



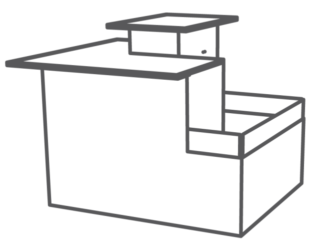
Category Costs	SIP ($/sq ft)	Stick Frame ($/sq ft)	Additional Cost of SIPs
Materials	$7.76	$5.00	$2.76
Equipment	$0.33	$0.00	$0.33
Schedule Savings Construction Loans	-$0.08	$0.00	-$0.08
Transportation	$0.16	$0.50	-$0.34
Energy Cost	$0.85	$1.00	-$0.15
Direct Labor	$1.36	$3.70	-$2.34
Total	**$10.38**	**$10.20**	**$0.18**

Simple Pitched Roof



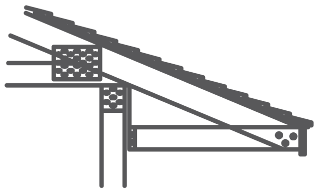
Category Costs	SIP ($/sq ft)	Stick Frame ($/sq ft)	Additional Cost of SIPs
Materials	$7.08	$4.79	$2.29
Equipment	$0.33	$0.00	$0.33
Schedule Savings Construction Loans	-$0.08	$0.00	-$0.08
Transportation Unloading	$0.16	$0.48	-$0.32
Energy Cost	$0.85	$1.00	-$0.15
Direct Labor	$1.34	$3.71	-$2.37
Total	**$9.68**	**$9.98**	**-$0.30**

Flat Roof



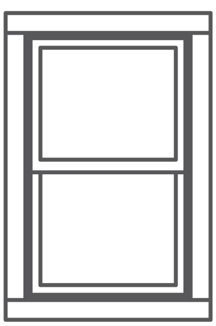
Category Costs	SIP ($/sq ft)	Stick Frame ($/sq ft)	Additional Cost of SIPs
Materials	$7.08	$3.21	$3.87
Equipment	$0.33	$0.00	$0.33
Schedule Savings Construction Loans	-$0.08	$0.00	-$0.08
Transportation Unloading	$0.16	$0.32	-$0.16
Energy Cost	$0.85	$1.00	-$0.15
Direct Labor	$1.89	$3.71	-$1.82
Total	**$10.23**	**$8.24**	**$1.99**

Roof Overhangs



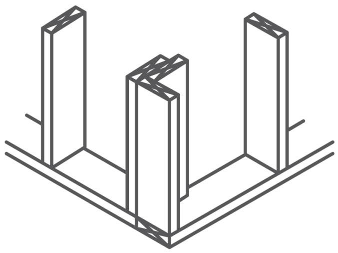
Category Costs	SIP ($/sq ft)	Stick Frame ($/sq ft)	Additional Cost of SIPs
Materials	$7.31	$4.08	$3.23
Equipment	$0.33	$0.00	$0.33
Schedule Savings Construction Loans	-$0.08	$0.00	-$0.08
Transportation Unloading	$0.16	$0.41	-$0.25
Energy Cost	$0.85	$1.00	-$0.15
Direct Labor	$1.34	$3.71	-$2.37
Total	**$9.91**	**$9.20**	**$0.71**

Apertures



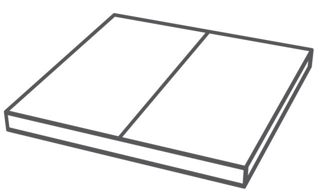
Category Costs	SIP ($/sq ft)	Stick Frame ($/sq ft)	Additional Cost of SIPs
Materials	$6.45	$2.26	$4.19
Equipment	$0.33	$0.00	$0.33
Schedule Savings Construction Loans	-$0.08	$0.00	-$0.08
Transportation Unloading	$0.16	$0.23	-$0.07
Energy Cost	$0.85	$1.00	-$0.15
Direct Labor	$0.00	$2.64	-$2.64
Total	**$7.71**	**$6.13**	**$1.58**

Straight Wall



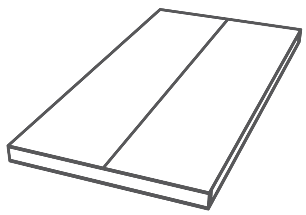
Category Costs	**SIP ($/sq ft)**	**Stick Frame ($/sq ft)**	**Additional Cost of SIPs**
Materials	$6.45	$2.26	$4.19
Equipment	$0.33	$0.00	$0.33
Schedule Savings Construction Loans	-$0.08	$0.00	-$0.08
Transportation Unloading	$0.16	$0.23	-$0.07
Energy Cost	$0.85	$1.00	-$0.15
Direct Labor	$1.02	$2.64	-$1.62
Total	**$8.73**	**$6.13**	**$2.60**

Short Span Floor



Category Costs	**SIP ($/sq ft)**	**Stick Frame ($/sq ft)**	**Additional Cost of SIPs**
Materials	$7.08	$4.02	$3.06
Equipment	$0.33	$0.00	$0.33
Schedule Savings Construction Loans	-$0.08	$0.00	-$0.08
Transportation Unloading	$0.16	$0.40	-$0.24
Energy Cost	$0.85	$1.00	-$0.15
Direct Labor	$1.89	$3.24	-$1.35
Total	**$10.23**	**$8.66**	**$1.57**

Long Span Floor



Category Costs	SIP ($/sq ft)	Stick Frame ($/sq ft)	Additional Cost of SIPs
Materials	$7.62	$4.80	$2.82
Equipment	$0.33	$0.00	$0.33
Schedule Savings Construction Loans	-$0.08	$0.00	-$0.08
Transportation Unloading	$0.16	$0.48	-$0.32
Energy Cost	$0.85	$1.00	-$0.15
Direct Labor	$1.89	$3.24	-$1.35
Total	**$10.77**	**$9.52**	**$1.25**

Comparative Cost Matrix Overview

The Comparative Cost Matrix is constructed to be as easy to use as possible for the designer testing how much more their building would potentially be. The designer decides which parts of their small scale residential home correspond with which Building Elements. They then determine Material Square Footage of the house and plug those values into column three of the Matrix (x Surface Area). By multiplying across (SIP vs Stick x Surface Area) the Cost Difference can be determined for each Building Element. Finally, the designer determines the total Cost Difference by adding all of the values in the fourth column, this value is a rough approximation of the total additional cost of building with Structural Insulated Panels instead of typical stick frame construction for a home. The designer can then observe which Building Elements are adding the most and least additional cost and determine if they warrant the additional expense. It is important to note that these cost estimates only apply to small scale residential homes, larger houses over 1000 square feet would possess slightly different Category and Building Element costs.

Comparative Cost Matrix

Building Element	SIP vs Stick ($ / MSF)	x Surface Area (MSF)	= Cost Difference
Simple Pitched Roof	-$0.30		
Complex Pitched Roof	$0.18		
Flat Roof	$1.99		
Roof Overhang	$0.71		
Dormer	$1.89		
Straight Wall	$2.60		
Aperture	$1.58		
Long Span Floor	$1.25		
Short Span Floor	$1.57		
Total	-	100%	**$**

Design

In order to both test the Comparative Cost Matrix as well as provide a working example of how to use it I have assessed the following three designs for how much they would additionally cost if constructed with SIPs. To test a wide variety of Building Elements I have used a Bungalow, a Saltbox, and a Modern small scale residential home. Each separate home was based on features common to that style and each is roughly 1000 square feet. The houses have a brief description of the style, a set of example design documents (see Figures 4-18), and finally a cost analysis. The SIP panels are drawn on each image to give an understanding of how the design would be constructed. The panel sizes are designated by the author based on general building principals and construction techniques with SIPs; however, typically this would be done by digital modeling through specialized software in order to maximize efficiency of material (i.e. minimize waste). See Appendix A for an abridged construction manual.

Each home was assessed for the additional cost they would incur if built with SIPs instead of stick frame construction. A completed Cost Matrix provides an estimate of the difference in cost when using different building elements in each style; it also gives an example of how design can impact cost. See Tables 24-26. The design drawings are at ⅛” = 1’ scale.

The Bungalow

Bungalows are a craftsman style home possessing large roofs with a low pitch, deep overhangs, small apertures, and a prominent front porch; it was originally derived by the British from the Indian "bangla"—a small single-story hut for wayfarers (White 1923). The porch is often somewhat ornate while the main house is more restrained. They are homes that are readily found in sizes under 1000 square feet and have a floor plan that accomplishes an efficient use of space. The walls are generally short and the roof simple, the overall shape is almost square. Windows are typically somewhat small and fairly square with a vertical orientation. The interior floor plan is often divided into smaller, separate rooms (White 1923).

The Bungalow is simple to build with structural insulated panels. Almost the entirety of the building envelope is well insulated since the small apertures don't need additional reinforcement with dimensional lumber. The interior walls and porch are both stick framed to reduce cost in locations where the superior quality of SIPs is not needed. The small roof is constructed of clear-span SIPs without a center ridge beam. SIPs allow the Bungalow to have cathedral ceilings if desired giving the illusion of additional space in a compact home.

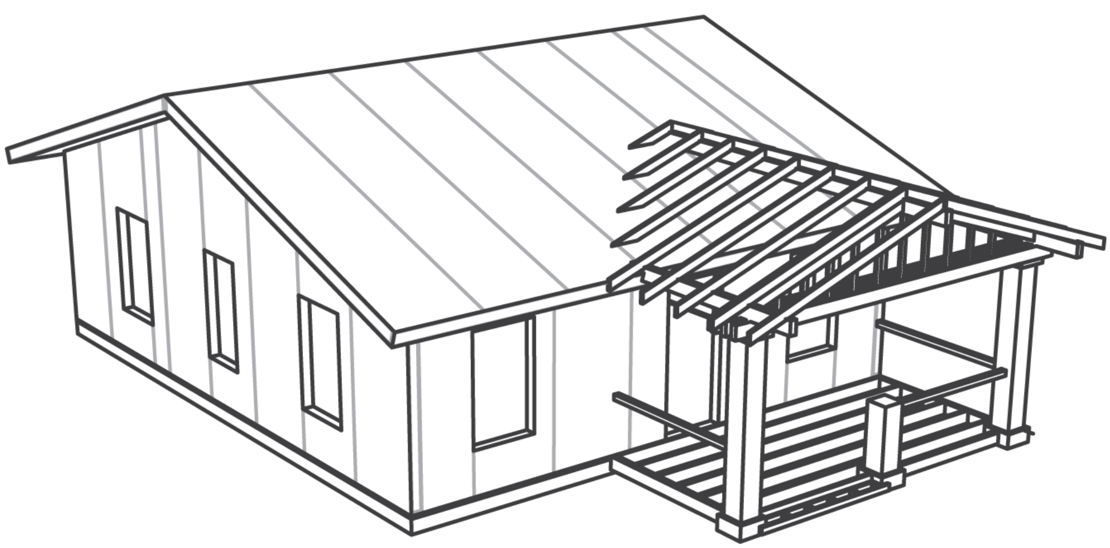


Figure 4: Bungalow Perspective (Author 2015)

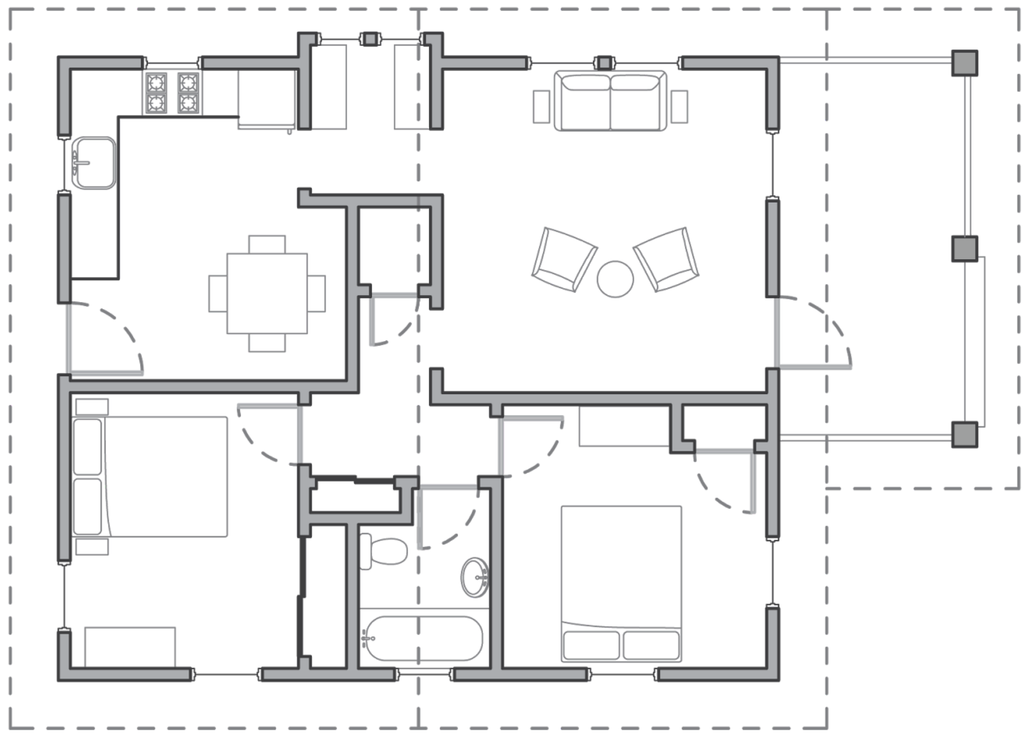


Figure 5: Bungalow Floor Plan - Ground Floor (Author 2015)

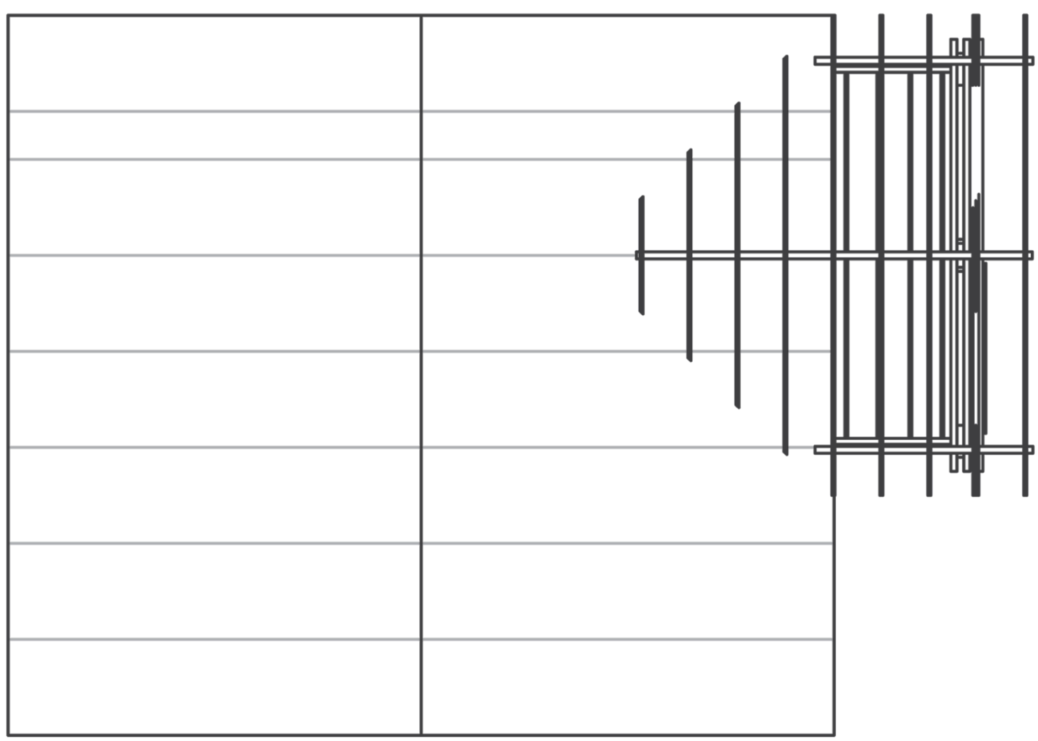
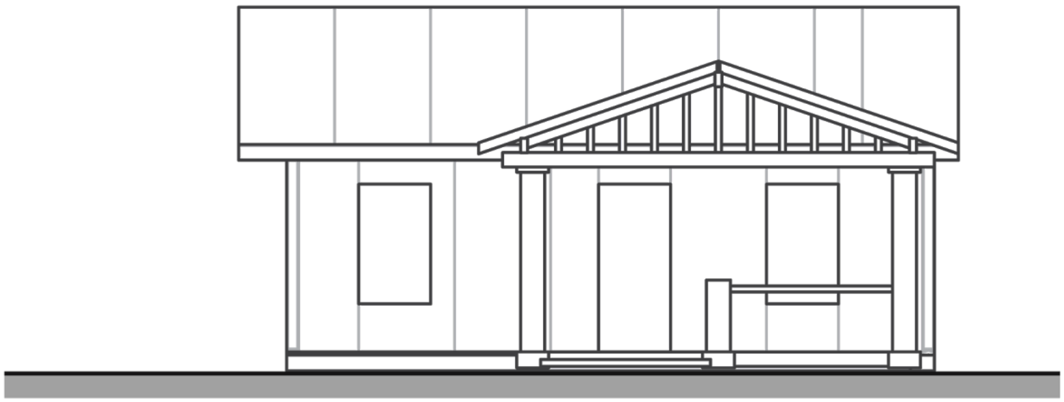


Figure 6: Bungalow Roof Plan (Author 2015)



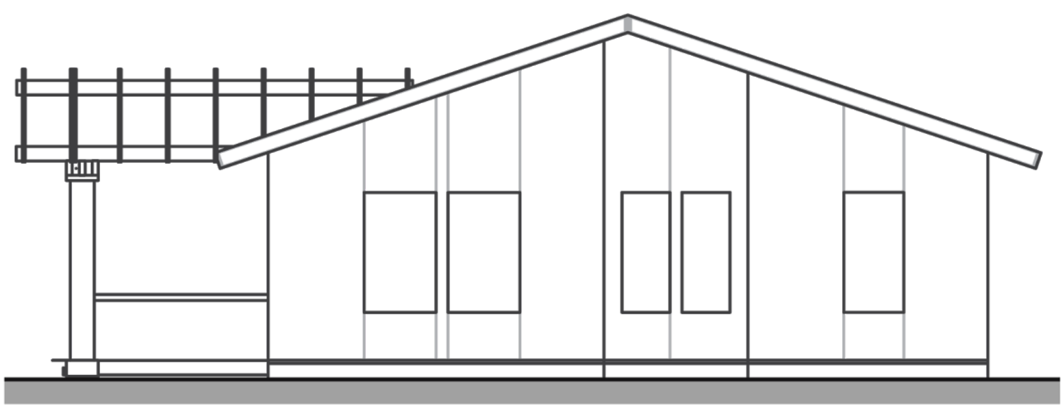


Figure 7: Bungalow Elevations (Author 2015)

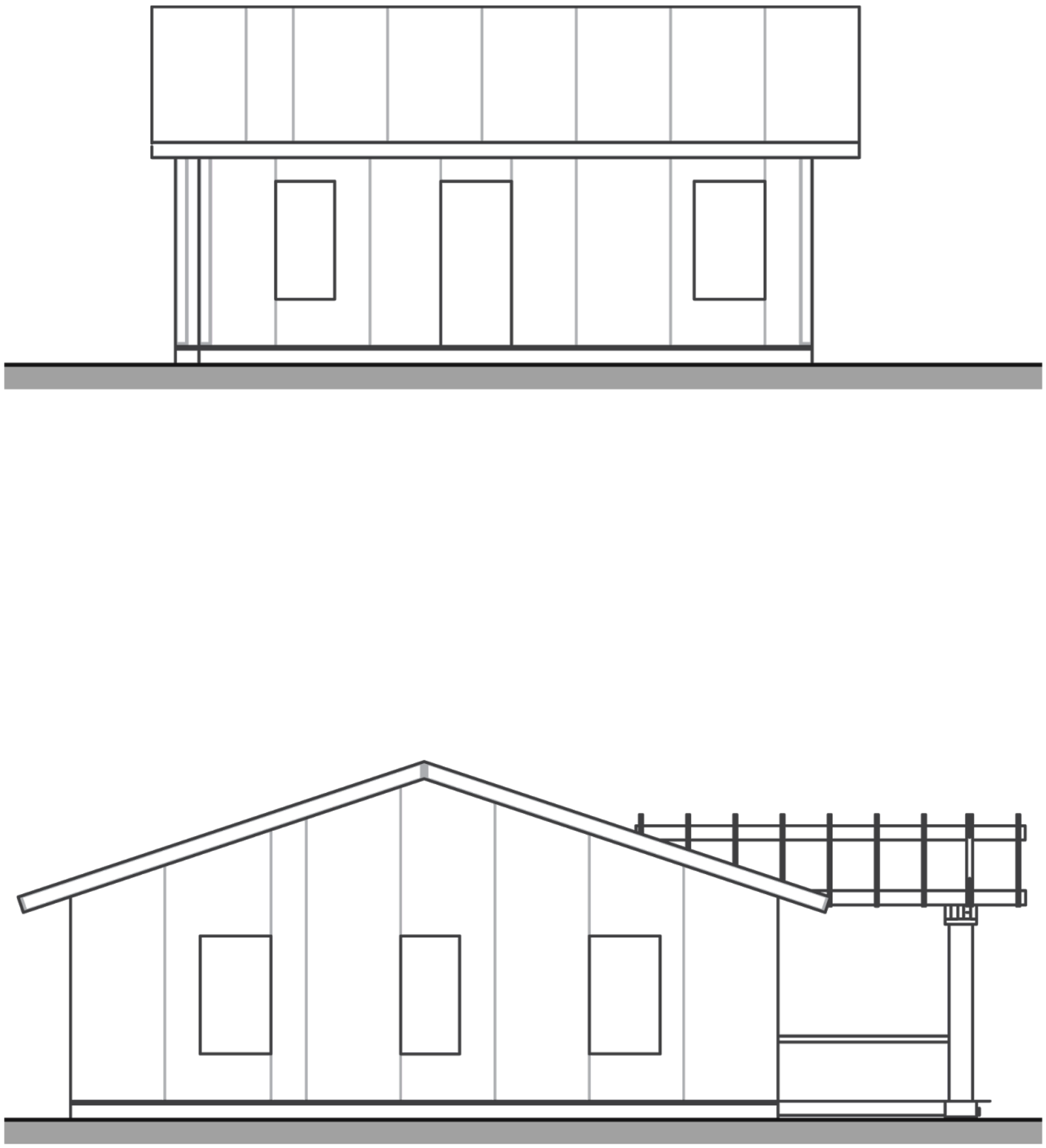


Figure 8: Bungalow Elevations (Author 2015)

Table 24 | Bungalow SIP Cost Comparison

Building Element	**SIP vs Stick ($/ MSF)**	**x Surface Area (MSF)**	**= Cost Difference**
Simple Pitched Roof	-$0.30	822	-$246.60
Complex Pitched Roof	$0.18		
Flat Roof	$1.99		
Roof Overhang	$0.71	266	$188.86
Dormer	$1.89		
Straightt Wall	$2.60	903	$2,347.80
Aperture	$1.58	205	$323.90
Long Span Floor	$1.25		
Short Span Floor	$1.57	725	$1,138.25
Total	-	100%	**$3,752.21***

*With a gross total area of 780 square feet the Bungalow would end up costing approximately an additional $4.81 per building square foot.

The Saltbox

Saltboxes are a colonial style of home, they possess large and prominent roofs, shallow overhangs, small apertures, and no attached outdoor space. The name is derived from boxes that were used to store salt, the sloping lid resembled the unequal roofs (Doane 1970). The original saltboxes were constructed by adding a lean-to on the rear of a two-story house, in traditional saltbox homes the central fireplace was a strong and practical feature (Doane 1970). The home is often quite restrained, with little or no ornamentation; they were a purely functional house style. They are homes that are readily found in sizes under 1000 square feet and have a floor plan that accomplishes an efficient use of vertical space. The overall shape is derived from a necessity to shed snow and protect against cold winter winds and, the steeply pitched roof also allows for an opportunity to add a second story without adding an additional exterior rear wall. Windows are typically smaller and fairly square with a vertical orientation. The interior floor plan is often divided into smaller, separate rooms though a larger living space is found within modern saltoxes (Doane 1970).

The Saltbox is quite simple to build with structural insulated panels. Almost the entirety of the building envelope is well insulated since the small apertures don’t need additional reinforcement with dimensional lumber. The interior walls and second story floor are both stick framed to reduce cost in locations where the superior quality of SIPs is not needed. The large roof is constructed of clear-span SIPs with a center ridge beam. SIPs allow the Saltbox to take full advantage of its cathedral ceilings giving the additional space of a second floor in a compact home. The following design for a saltbox home flips the typical interior orientation on the ground floor, placing the front door on the single-story side to facilitate the addition of a third bedroom as well as adding a vaulted ceiling in the living room.

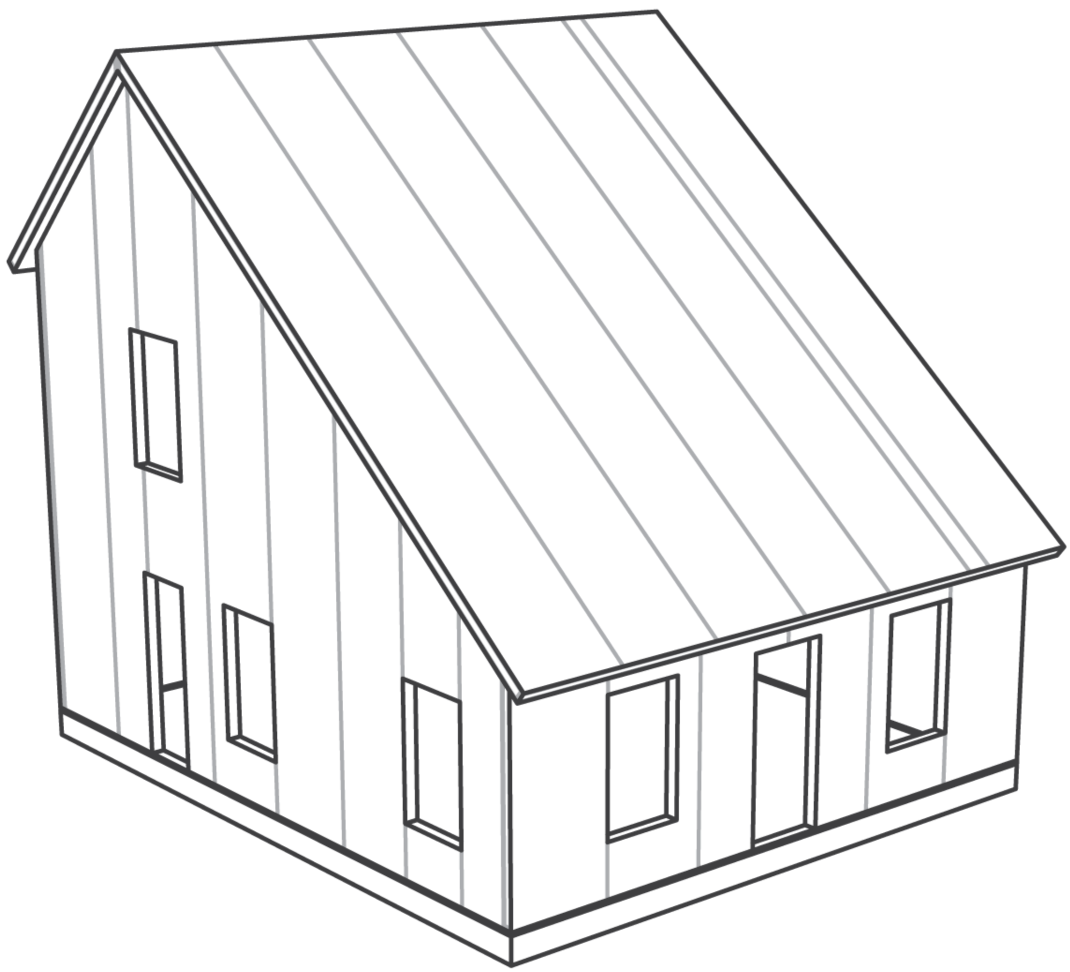


Figure 9: Saltbox Perspective (Author 2015)

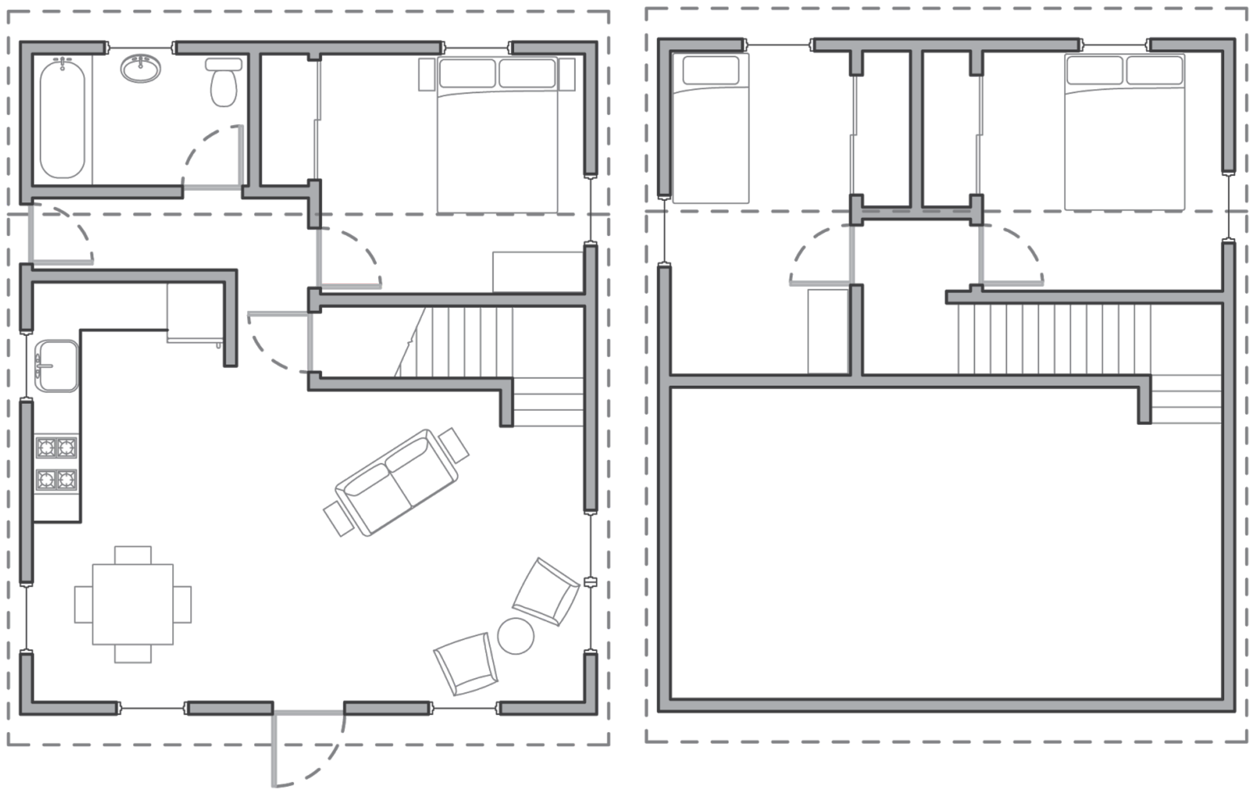


Figure 10: Saltbox Floor Plans - Ground Floor and Second Floor (Author 2015)

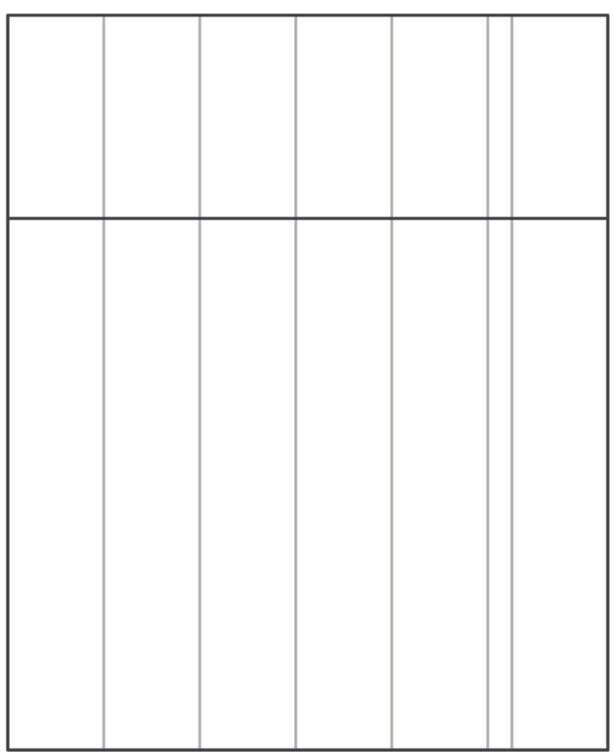


Figure 11: Saltbox Roof Plan (Author 2015)

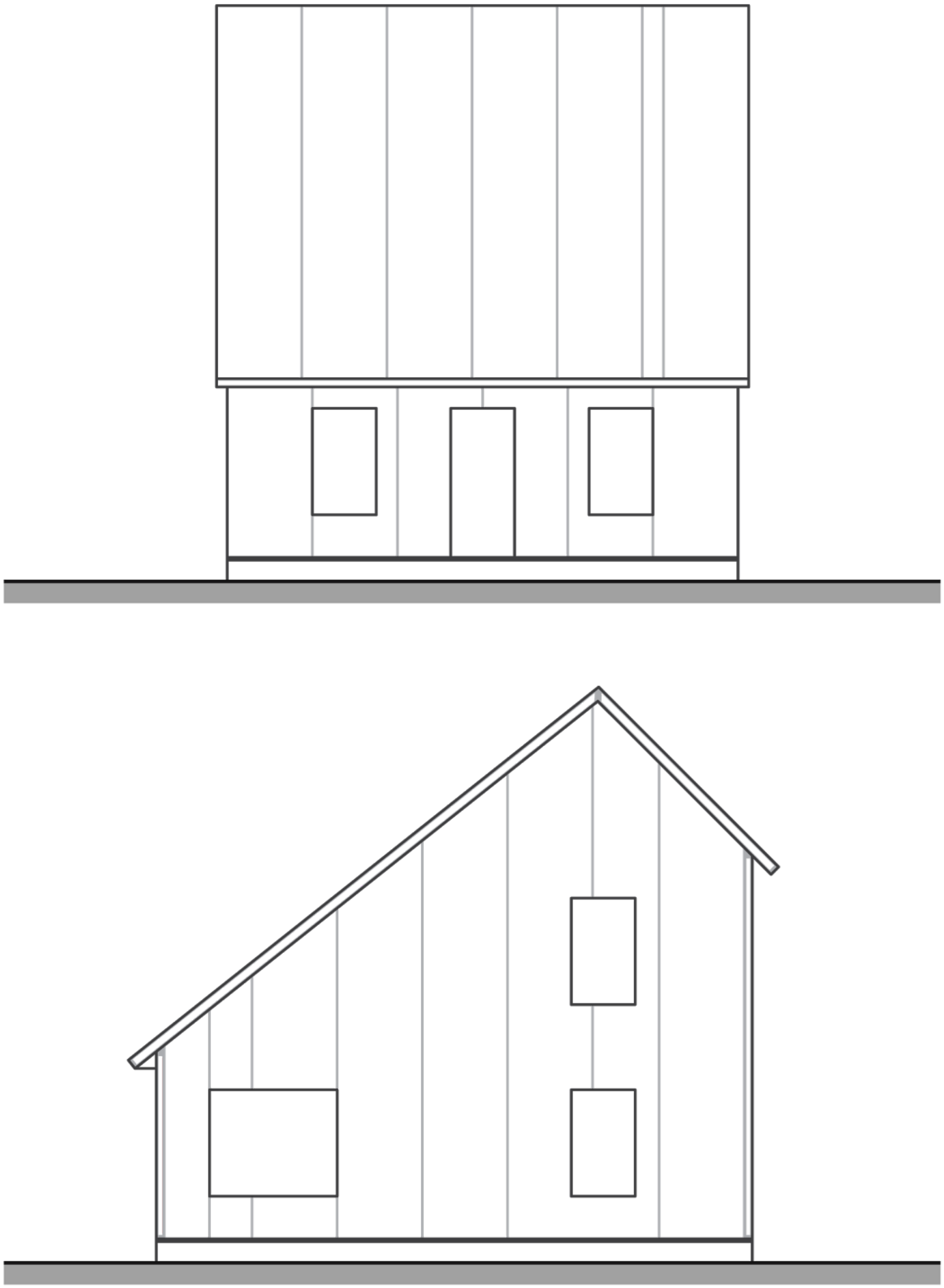


Figure 12: Saltbox Elevations (Author 2015)

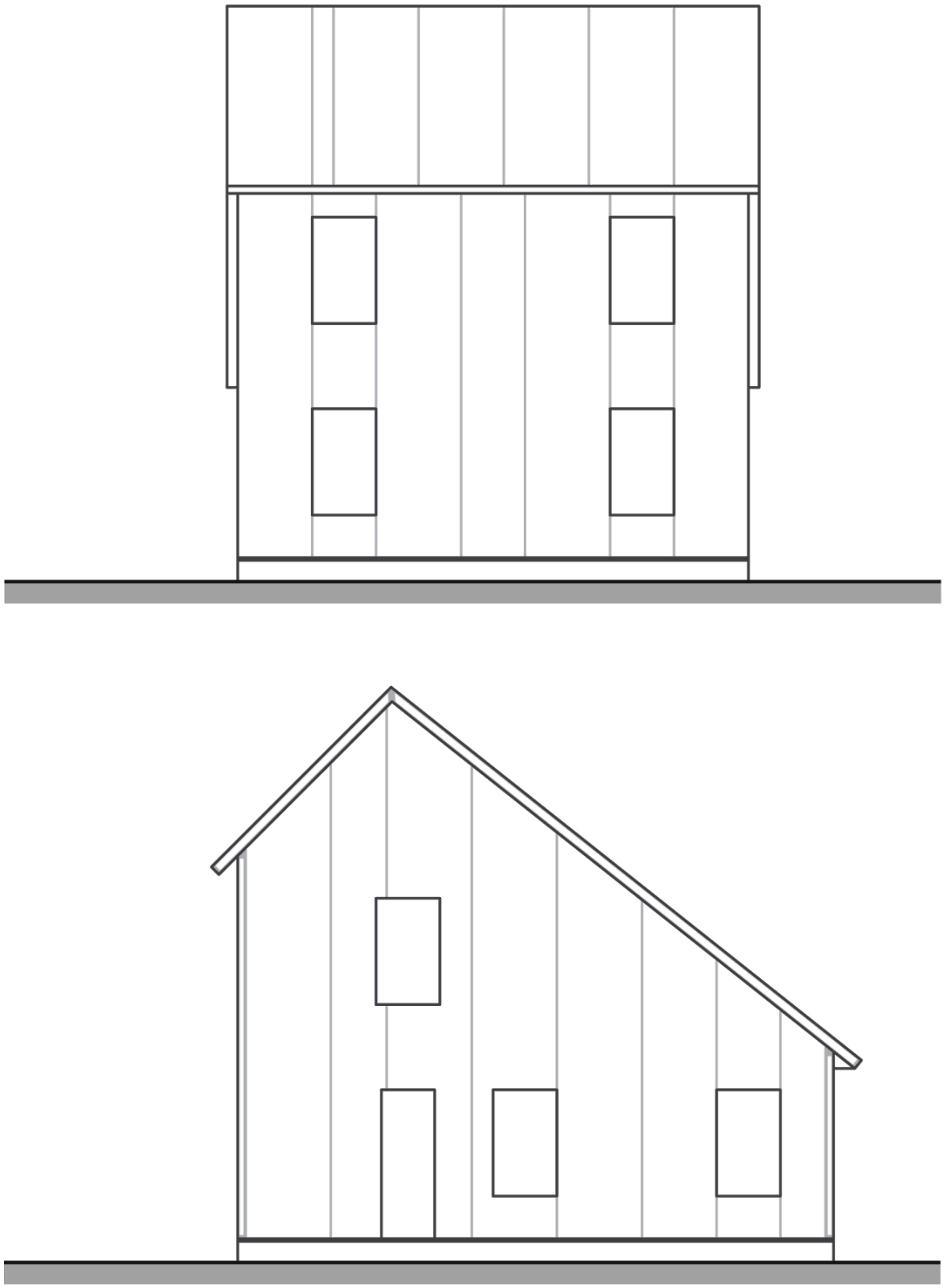


Figure 13: Saltbox Elevations (Author 2015)

Table 25 | Saltbox SIP Cost Comparison

Building Element	**SIP vs Stick ($ / MSF)**	**x Surface Area (MSF)**	**= Cost Difference**
Simple Pitched Roof	-$0.30	882	-$264.60
Complex Pitched Roof	$0.18		
Flat Roof	$1.99		
Roof Overhang	$0.71	122	$86.62
Dormer	$1.89		
Straight Wall	$2.60	1402	$3,645.20
Aperture	$1.58	234	$369.72
Long Span Floor	$1.25		
Short Span Floor	$1.57	621	$974.97
Total	-	100%	**$4,811.91***

*With a gross total area of 1202 square feet the Saltbox would end up costing approximately an additional $4.72 per building square foot.

The Modern

Modern style homes encompass a huge variety of housing types and different building elements; for this design the term “Modern” possesses flat roofs, both deep and shallow overhangs, large apertures, and a prominent second story balcony. The outdoor becomes more accessible and includes a covered entrance porch. It is often very restrained, with square construction and simple textures. They are homes that can be designed for all sizes and have an open floor plan that accomplishes an efficient use of space by minimizing separation between rooms. The walls are generally mid-height and the roof flat, the overall shape is often slightly complicated with bumpouts and subtracting spaces. Windows are typically large with either a vertical or horizontal orientation.

The Modern is simple to build with structural insulated panels. The building envelope loses some insulating properties since the large apertures need additional reinforcement with dimensional lumber resulting in thermal bridging in portions of the wall. The interior walls are both stick framed to reduce cost in locations where the superior quality of SIPs is not needed. The flat roof is constructed of long-span SIPs with a center ridge beam. The Modern design uses a platform-framing technique for the walls which makes the framing process easier.

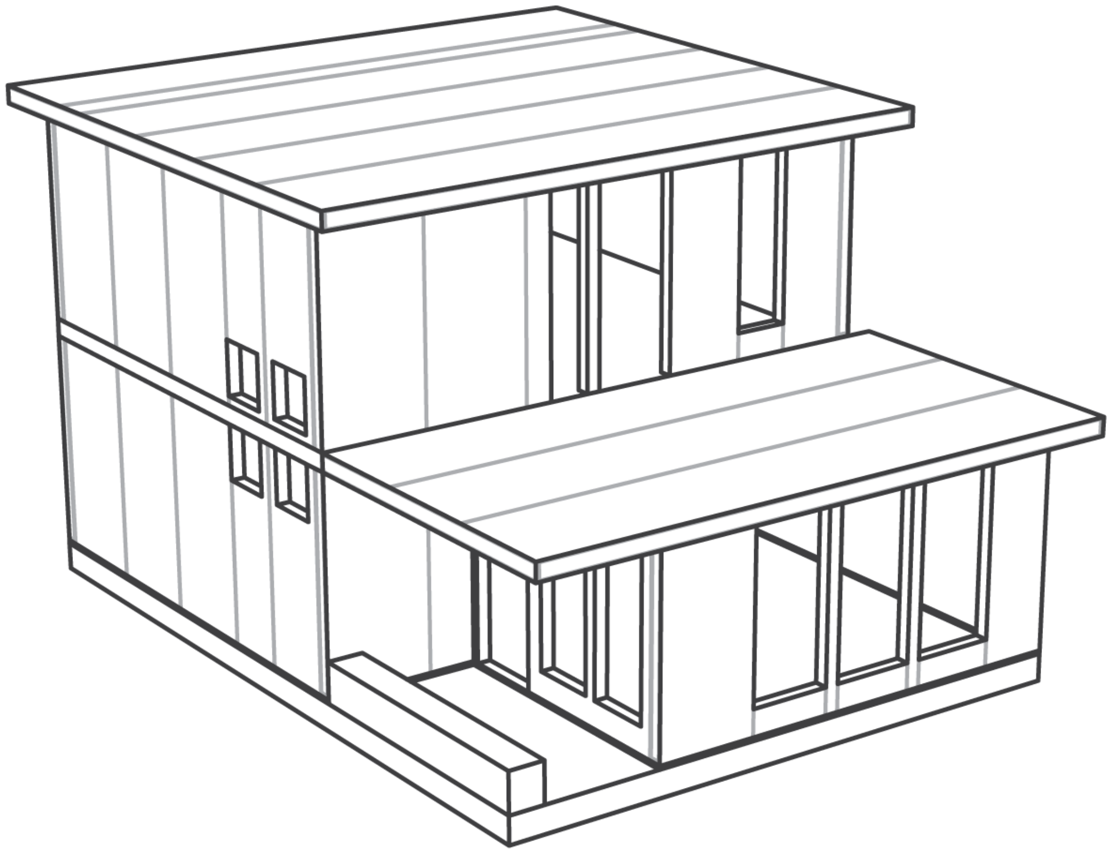


Figure 14: Modern Perspective (Author 2015)

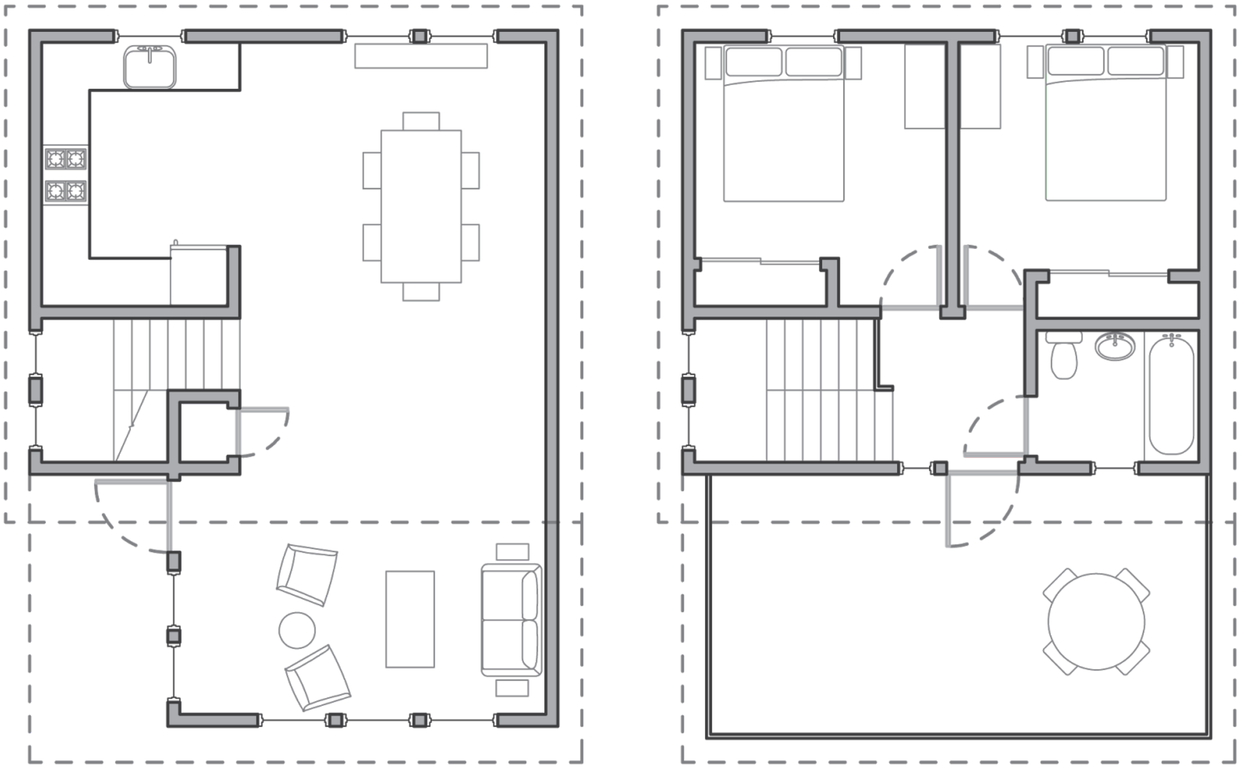


Figure 15: Modern Floor Plans - Ground Floor and Second Floor (Author 2015)

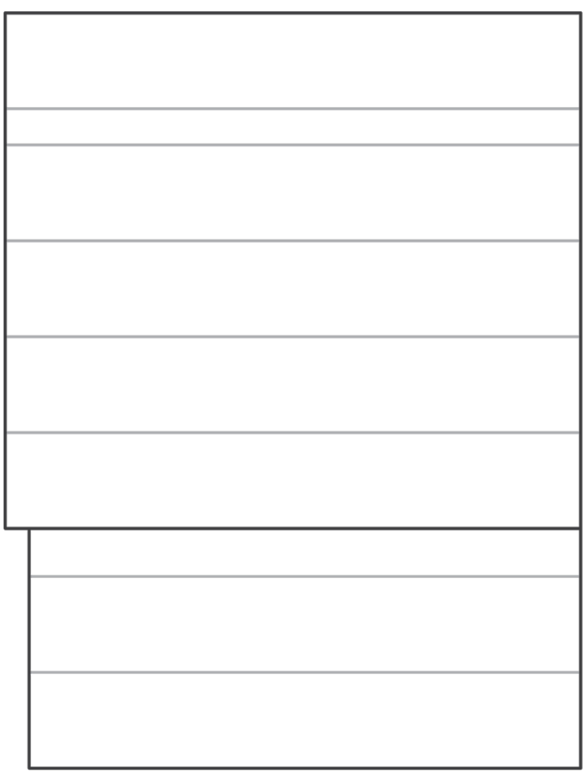


Figure 16: Modern Roof Plan (Author 2015)

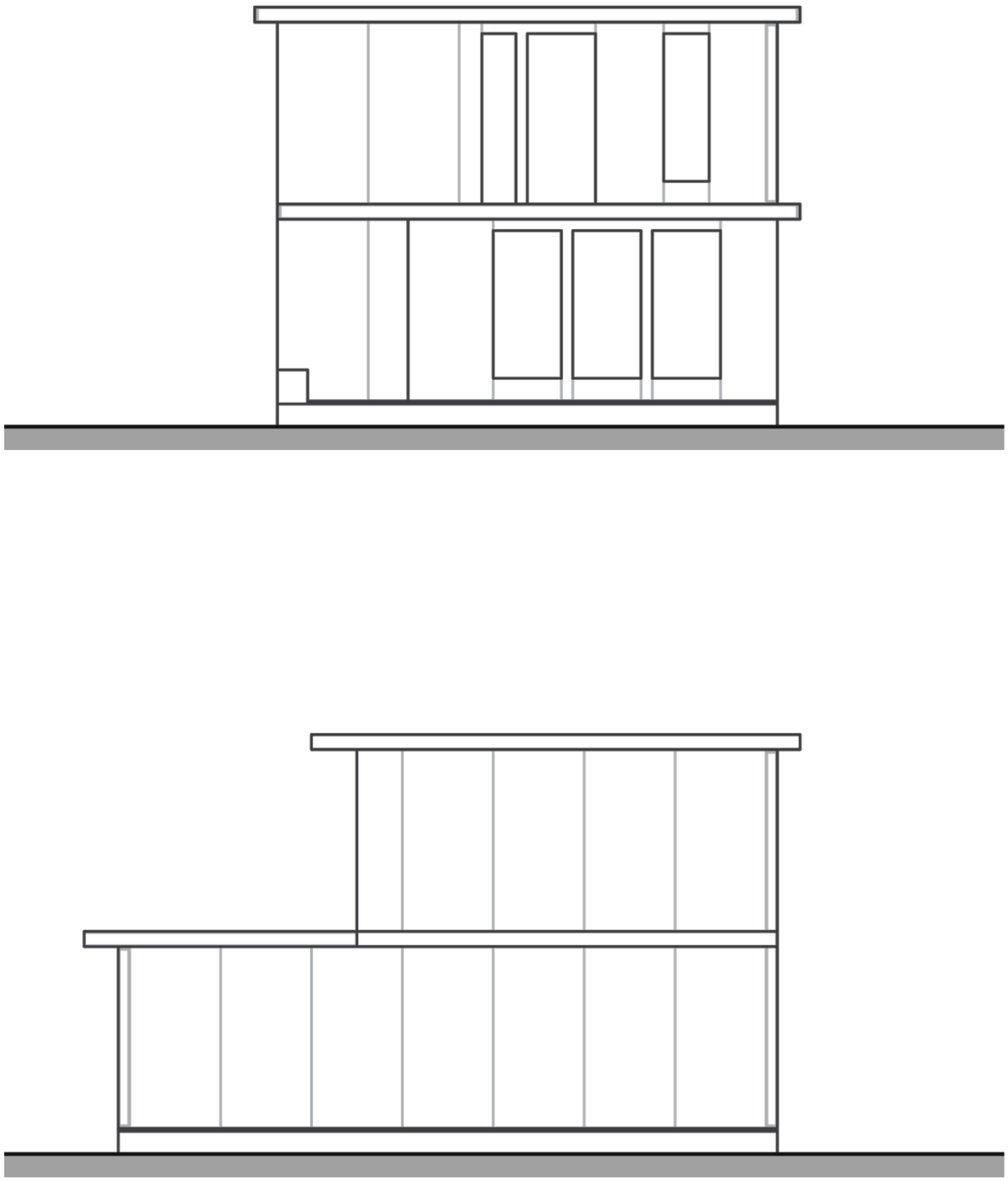


Figure 17: Modern Elevations (Author 2015)

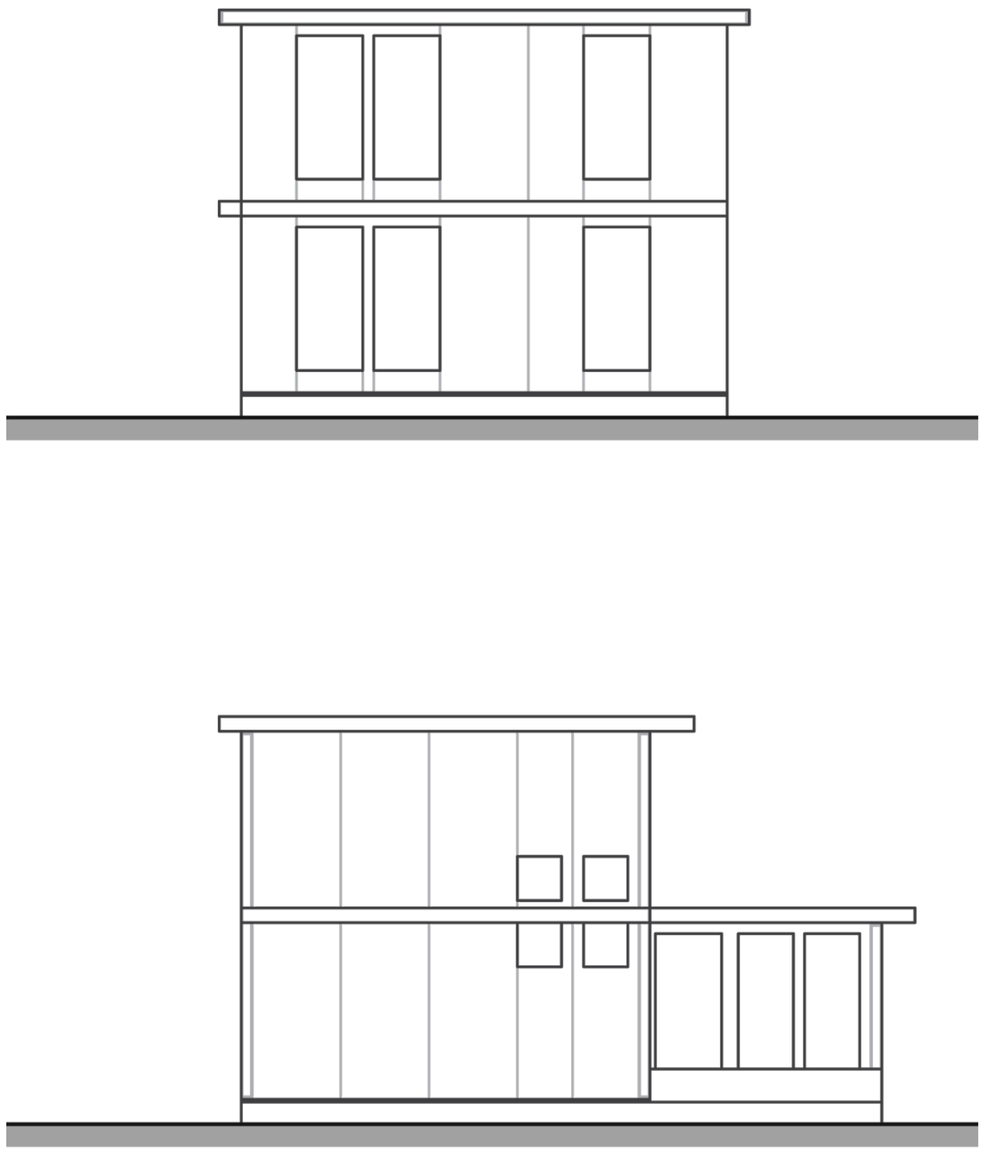


Figure 18: Modern Elevations (Author 2015)

Table 26 | Modern SIP Cost Comparison

Building Element	**SIP vs Stick ($ / MSF)**	**x Surface Area (MSF)**	**= Cost Difference**
Simple Pitched Roof	-$0.30		
Complex Pitched Roof	$0.18		
Flat Roof	$1.99	578	$1,150.22
Roof Overhang	$0.71	214	$151.94
Dormer	$1.89		
Straight Wall	$2.60	1110	$2,886.00
Aperture	$1.58	235	$371.30
Long Span Floor	$1.25		
Short Span Floor	$1.57	528	$828.96
Total	-	100%	**$5,388.42***

*With a gross total area of 985 square feet the Modern would end up costing approximately an additional $5.47 per building square foot.

Conclusion

An overview of the Comparative Cost Matrix reveals that is is not possible to construct a small scale Structural Insulated Panel home that is comparatively priced to the same house if it were built with stick frame construction methods. Only a single Building Element has a lower cost with SIPs than with stick frame even with energy savings over a five year period: Simple Pitched Roofs. This is the case for two reasons: the cost of pitched roofs constructed with a truss system is relatively expense (it is one of the most expensive elements of a stick frame building) and because there is a significant amount of labor involved in building a stick frame roof. However, this cost savings is not enough to offset the additional cost of all other building elements.

The total additional cost of using SIPs can be derived from my research as being approximately 10% greater on average, a number fairly similar to what found by Gagnon and Adams for industrial applications(1999), Wright (2011) Seward (2012) for large or average sized homes, and Christian et al. (2006) for SIP homes with donated materials. The average of the three different home designs tested (the Bungalow, Saltbox, and Modern) was an additional $4650 to build a small scale house with SIPs.

To make Structural Insulated Panels as economical as stick frame construction SIP manufacturers would need to reduce the material cost of SIPs. Material accounts for the vast majority of the additional cost of SIPs, they perform admirably in every other aspect from an economic standpoint. SIP manufacturing is a technology-driven industry—the software and machines required to produce SIPs accounts for a substantial expense that is relayed to the buyer (SIP manufacturer employee). By increasing the market share of Structural Insulated Panels manufacturers' fixed cost (i.e. the overhead for the software and machines) could potentially decrease per unit which in turn would reduce the material cost of SIPs. Alternatively, increasing the number of manufactures could also result in a decreased cost for SIPs as the additional competition could drive prices down.

While this study compared using 100% Structural Insulated Panels against 100% stick frame construction for the building envelope there is the option to reduce the degree of use with SIPs. If the designer were to specify only using SIPs for a Simple Roof then the overall cost of the envelope could be decreased (although freight would have to be factored into a smaller total material square footage which might negate the potential savings). A significant portion of the heat energy savings comes from the improved performance of the roof, this could result in a SIP roof on a stick frame home being an economically comparable option for improving the quality of home construction (Thomas et al. 2005). However, the cost analysis performed by this study assumed 100% SIP construction and decreasing the degree of use would alter the SIP costs per material square footage for each building element; thus, this option will only be mentioned for consideration and will not be assessed in depth.

There are three scenarios where building a small scale SIP home does make sense from an economic standpoint. If the building site is extremely remote, if the SIP materials are donated, or if there is an abundance of unskilled labor and skilled labor is in short supply all cases where the MSF cost of small scale SIPs as derived by this study would not hold true.

If the site is remote this greatly increases the cost of labor as well as other expenses such as transportation. A site that is one hour from the construction company's main office or branches can result in mistakes, poor quality construction, unskilled labor being utilized when skill labor is needed, equipment shortages, ineffective planning, and low productivity of laborers (Sidawi 2012). Using SIPs—which are more precise and can be erected in half the time—would greatly reduce these issues that result in additional construction costs (Sidawi 2012, Wright 2011).

Christian (2008), Christian et al (2006), and Mullens and Arif (2006) all benefited from having Structural Insulated Panels donated by a SIP manufacturer: this greatly decreased the cost of using SIPs. Material is the largest cost of SIPs—generally doubling the expense of stick frame materials—and having it donated makes it an extremely cost effective building method. If stick frame or SIP materials were to be donated to a project it would be more economical to use SIPs since they benefit from a large labor savings.

Mullens and Arif (2006) and Drain et al (2006) showed that there is very little difference in the time it takes for a skilled (in framing) laborer or an unskilled laborer to construct a SIP structure. If a large amount of unskilled labor is available—generally at a lower cost—then SIPs may be able to be more economical than stick frame construction.

These three scenarios are all unique and not the usual case. However, the additional cost of constructing a small scale Structural Insulated Panel home was shown to be relatively inconsequential compared to the total cost of the home. The designer has the ability—by utilizing the Comparative Cost Matrix established by this study—to determine if the superior performance of SIPs outweighs the additional costs, as well as if the building design can be adjusted to make it more cost effective by emphasizing Building Elements that have a small difference in cost between the construction methods.

Appendix A | Abridged Construction Manual

All images are by R-Control SIPs: Structural Insulated Panels Construction Manual (2012). These images help to describe common detailing involved in SIP construction to explain how airtight connections are made between panels for the walls, roof, and floors. They also describe how connections are made to a foundation for structural integrity, typical roof systems with SIPs, and aperture (door and window) systems.

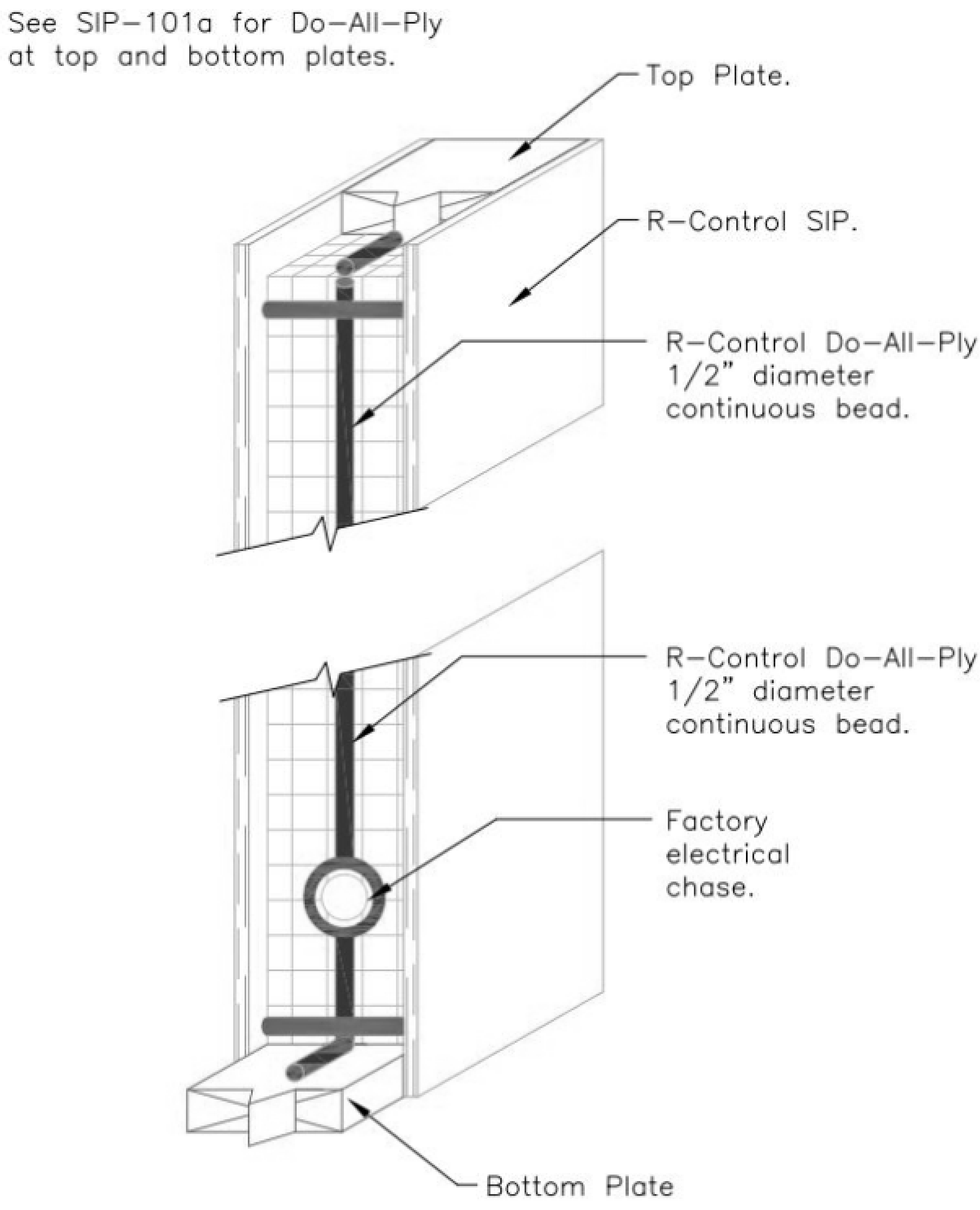


Figure 1: Wall Assembly and Sealing

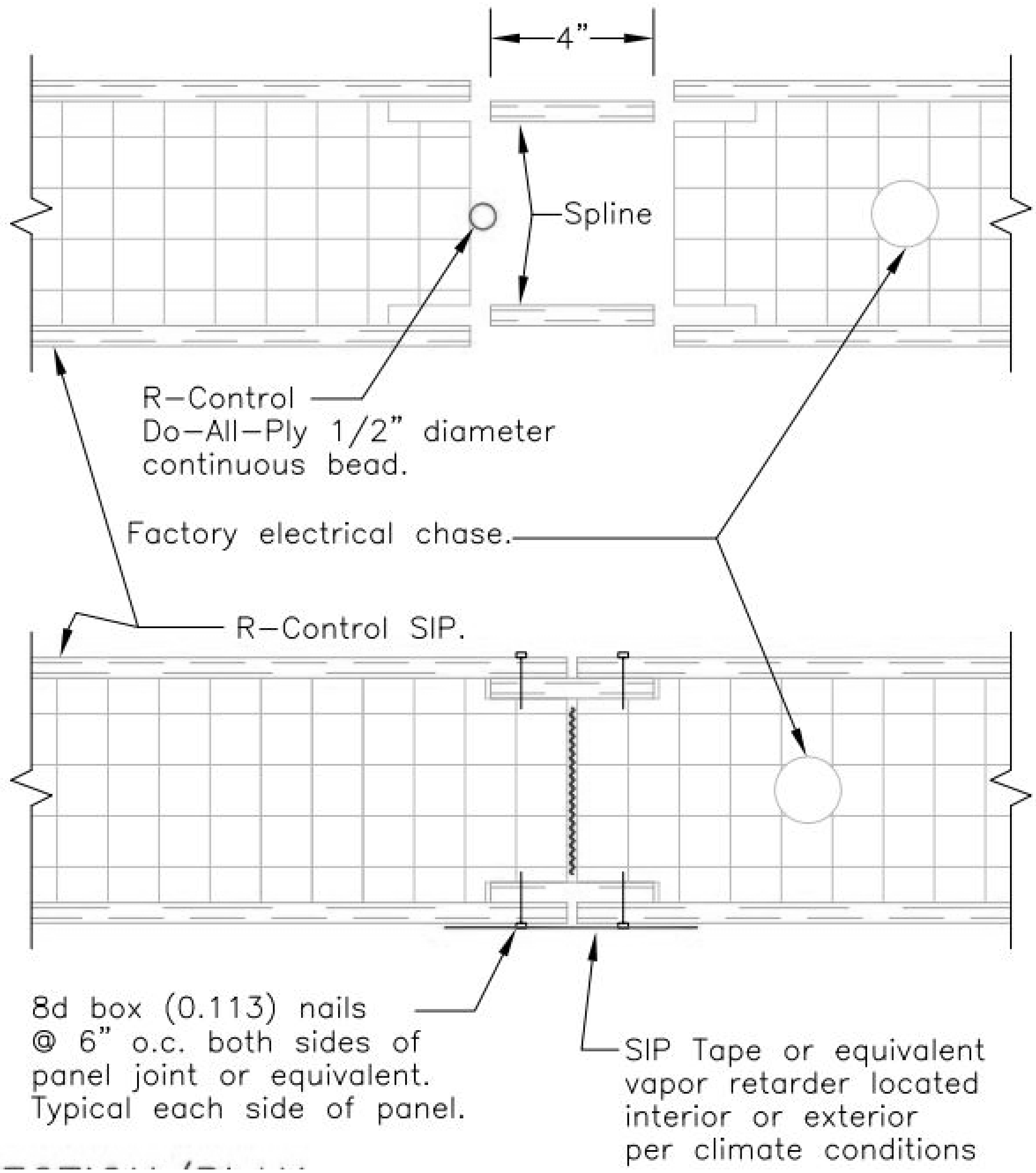


Figure 2: Foam Cutout + OSB Spline Wall Connection Method

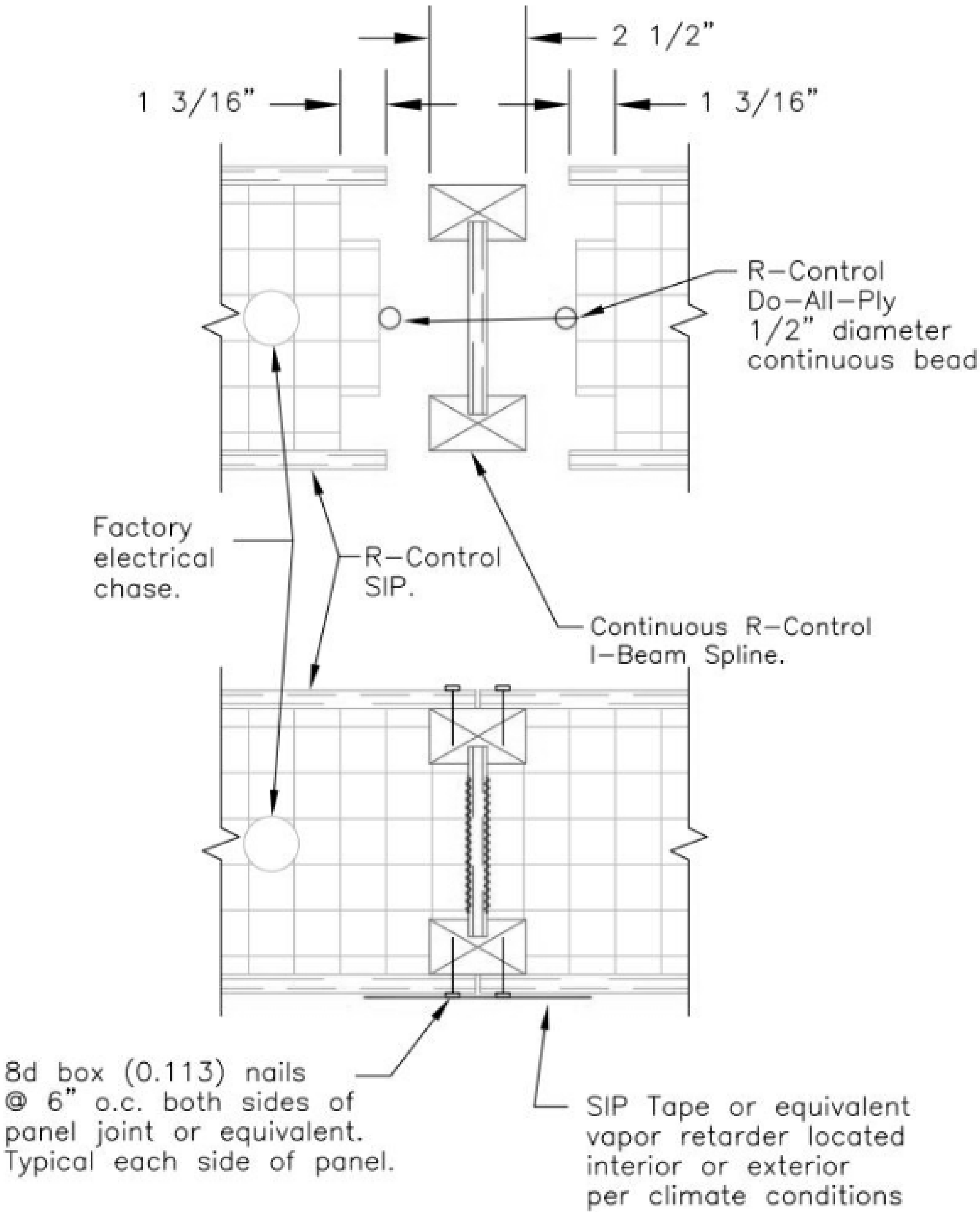


Figure 3: Foam Cutout + Wood I Beam Spline Wall Connection Method

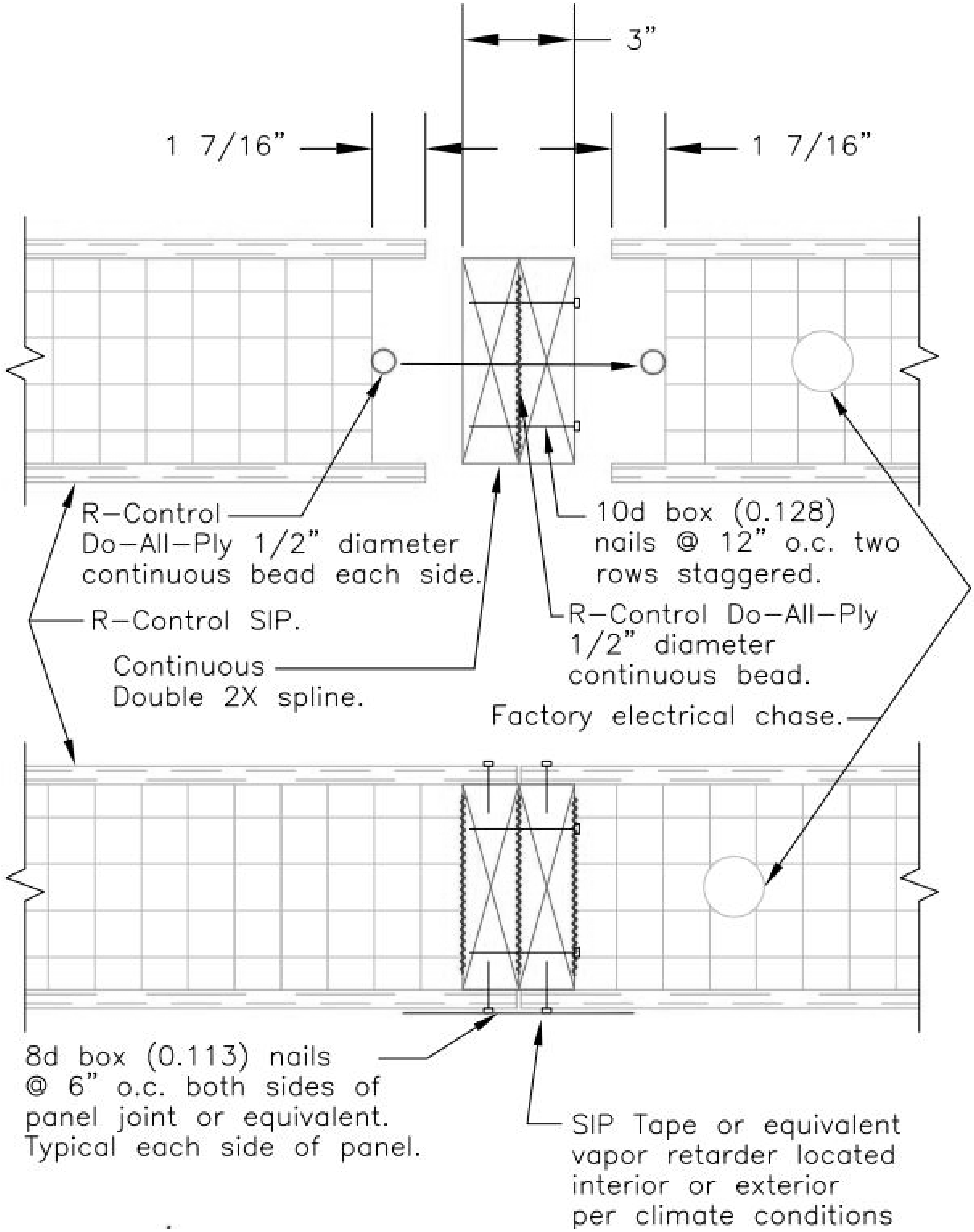


Figure 4: Foam Cutout + Dimensional Lumber Wall Connection Method

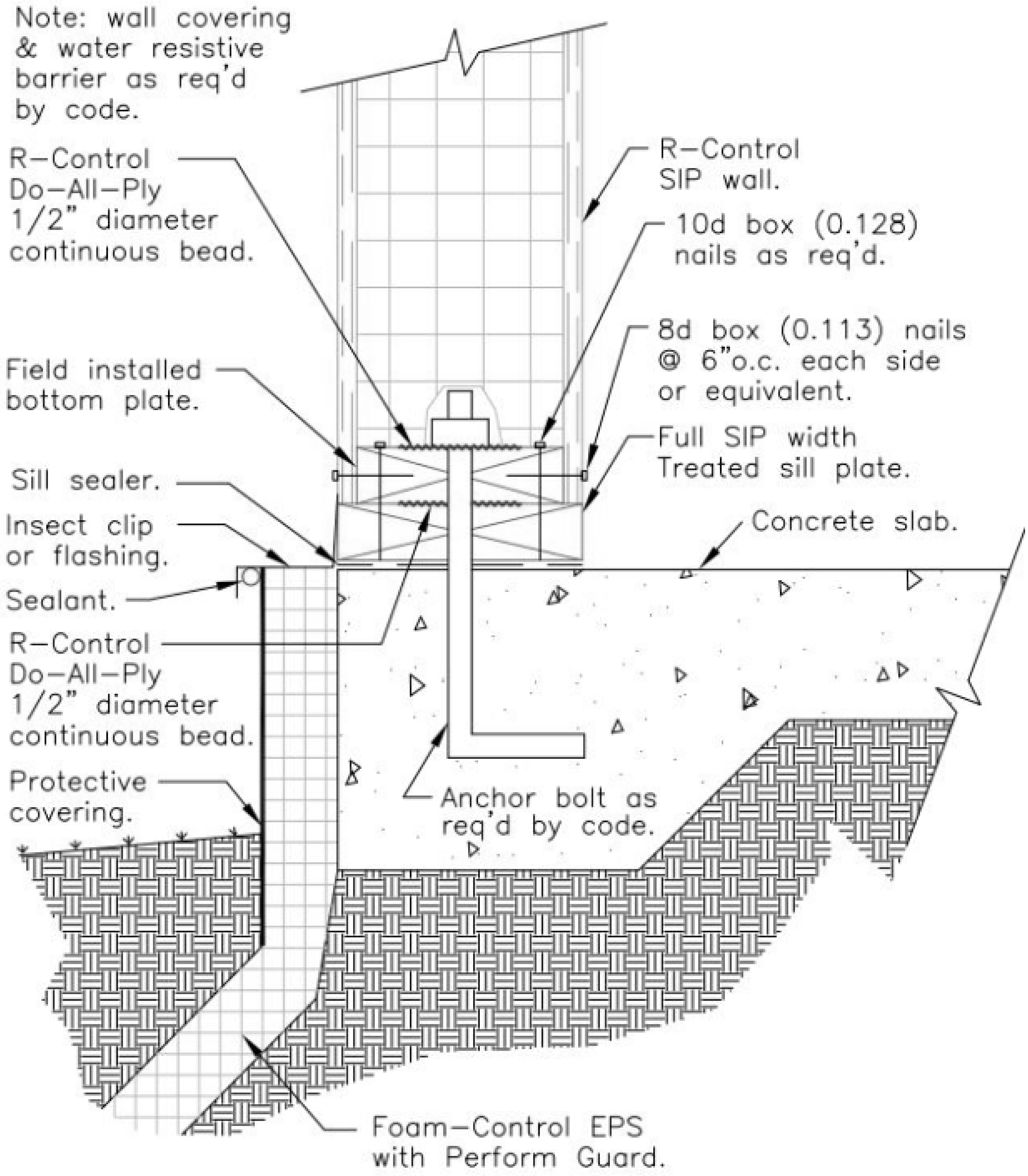


Figure 5: Foundation Connection

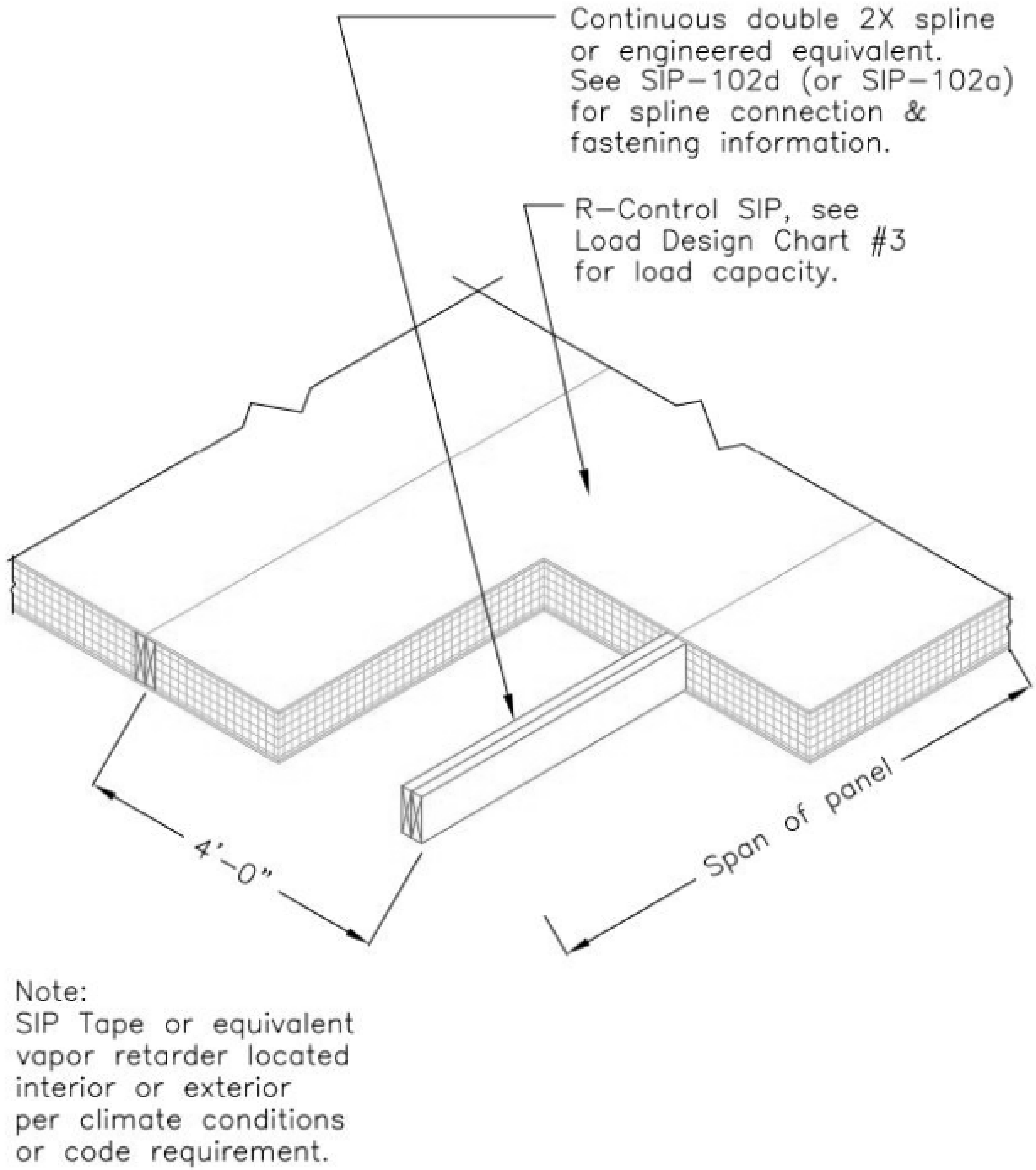


Figure 6: Floor + Roof Panel Assembly with Dimensional Lumber

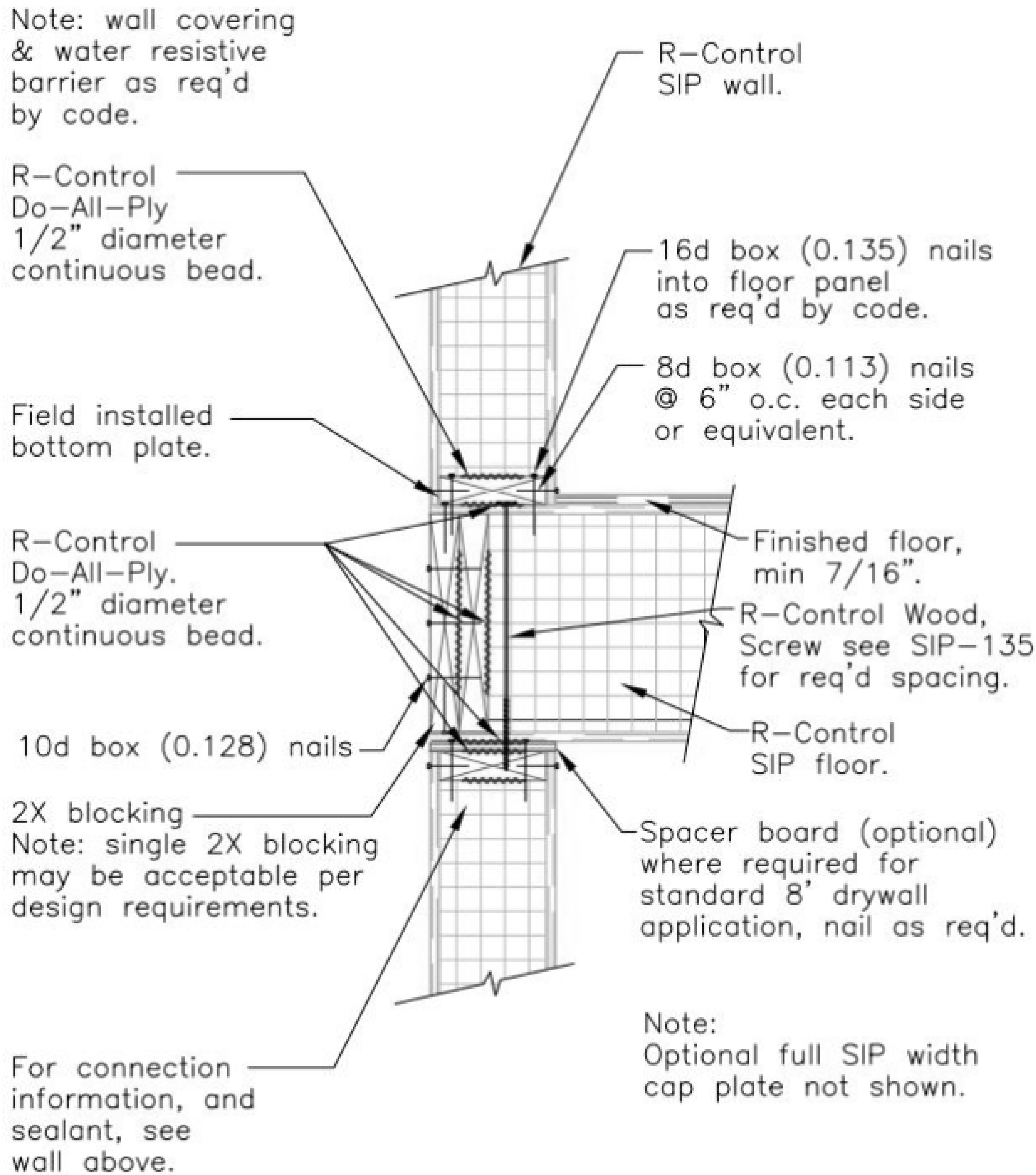


Figure 7: Second Floor Connection Platform Framing Method

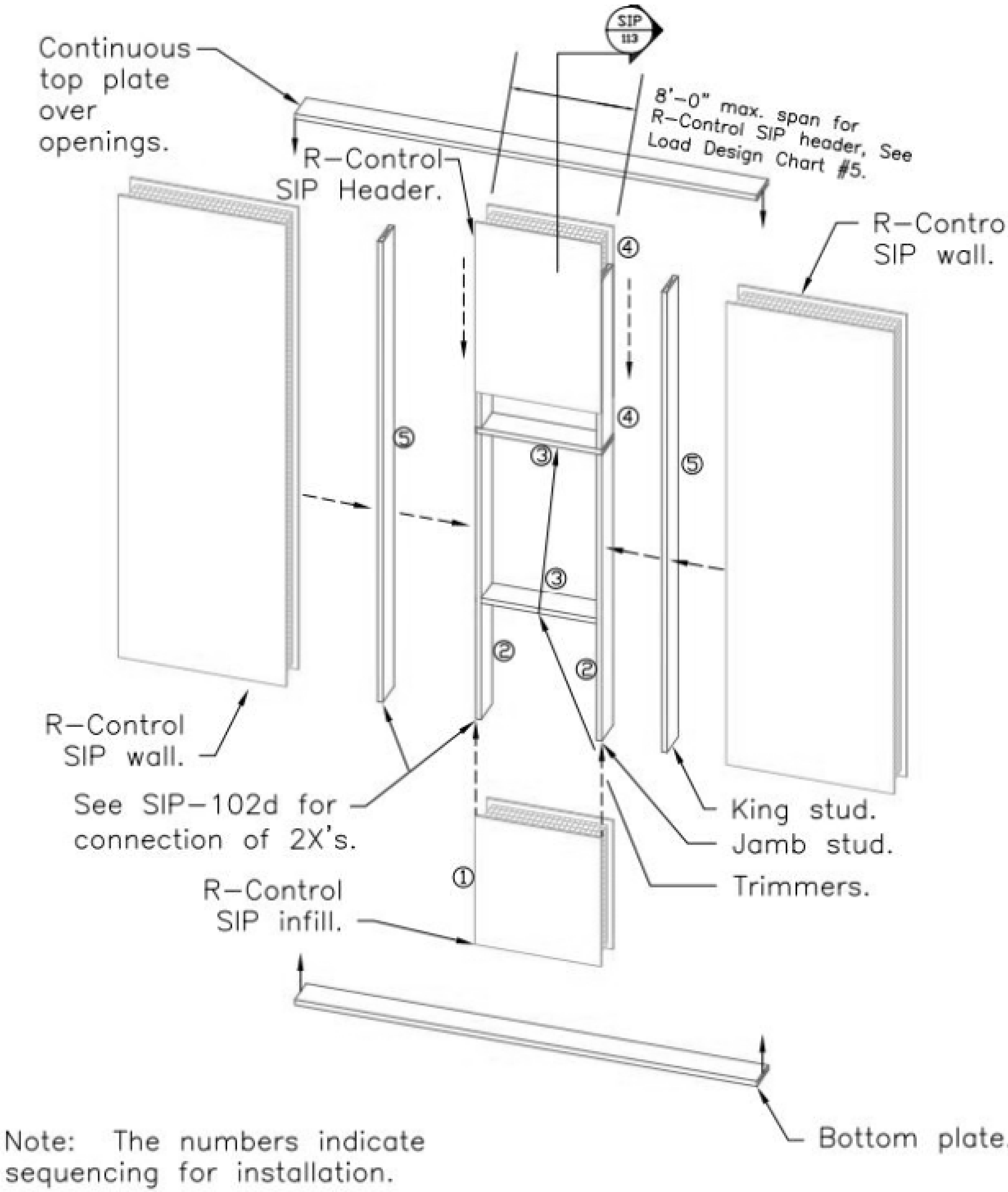


Figure 8: Window Framing with SIP Header Rough-in Method

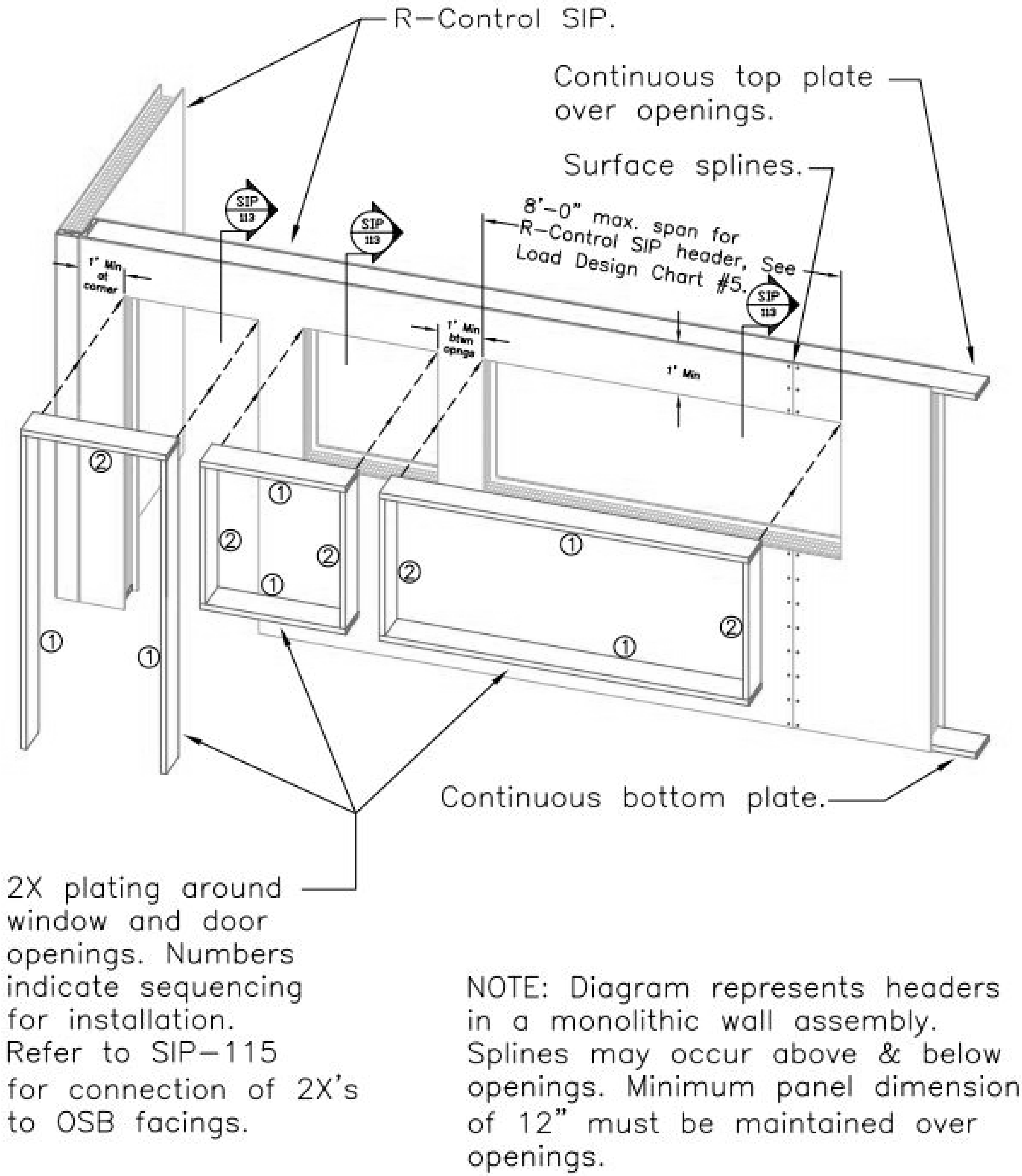


Figure 9: Cutout Window Rough-in Method

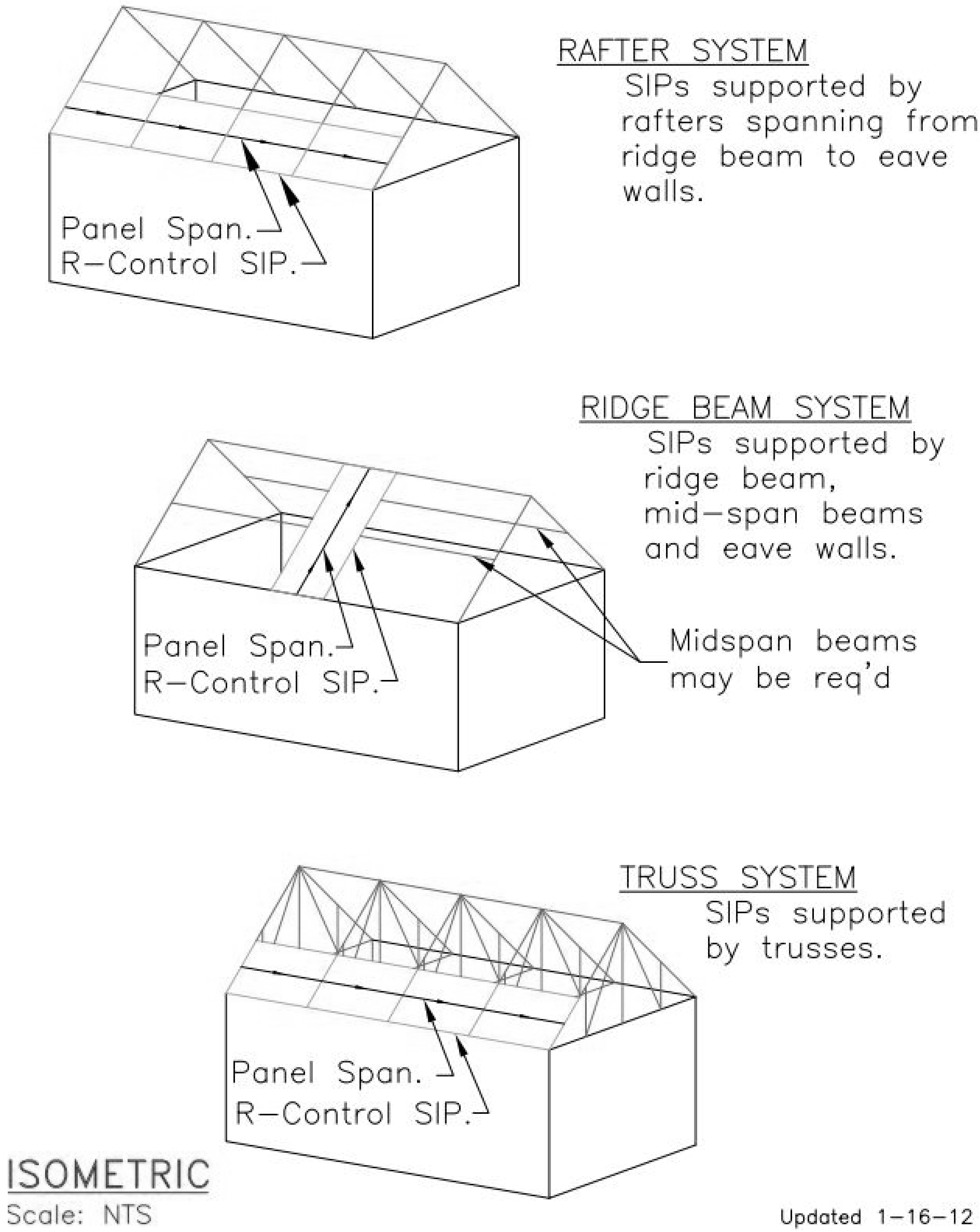


Figure 10: Roof Assembly Systems

Appendix B | Grand County SIP Design Documents

Construction drawings for the three cabin budgets reviewed for SIP pricing from Grand County SIPs. In order; Tapscott Cottage, Slockett Cottage, and Cedar View Cabin.

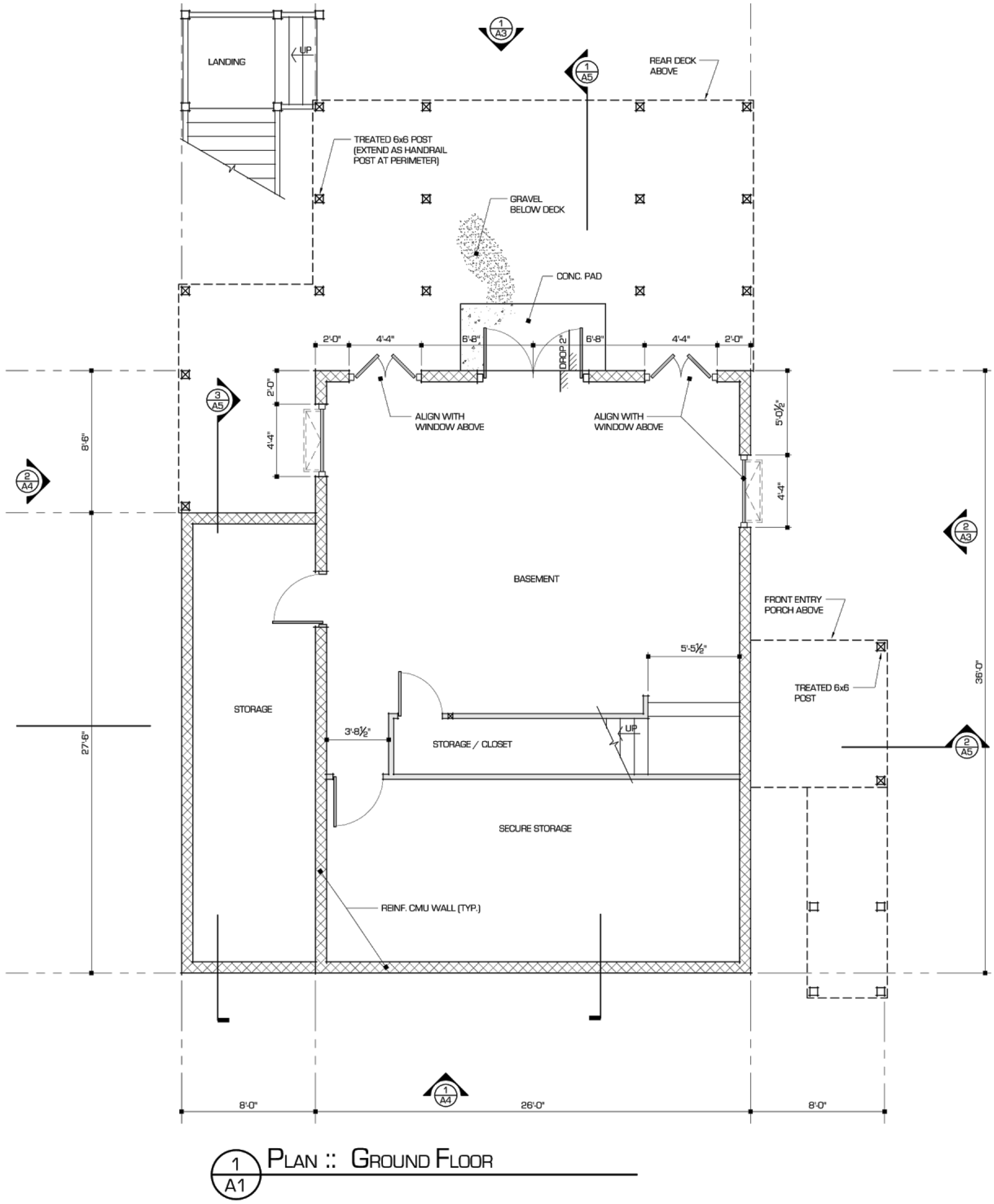


Figure 1: Tapscott Cottage - Ground Floor Plan

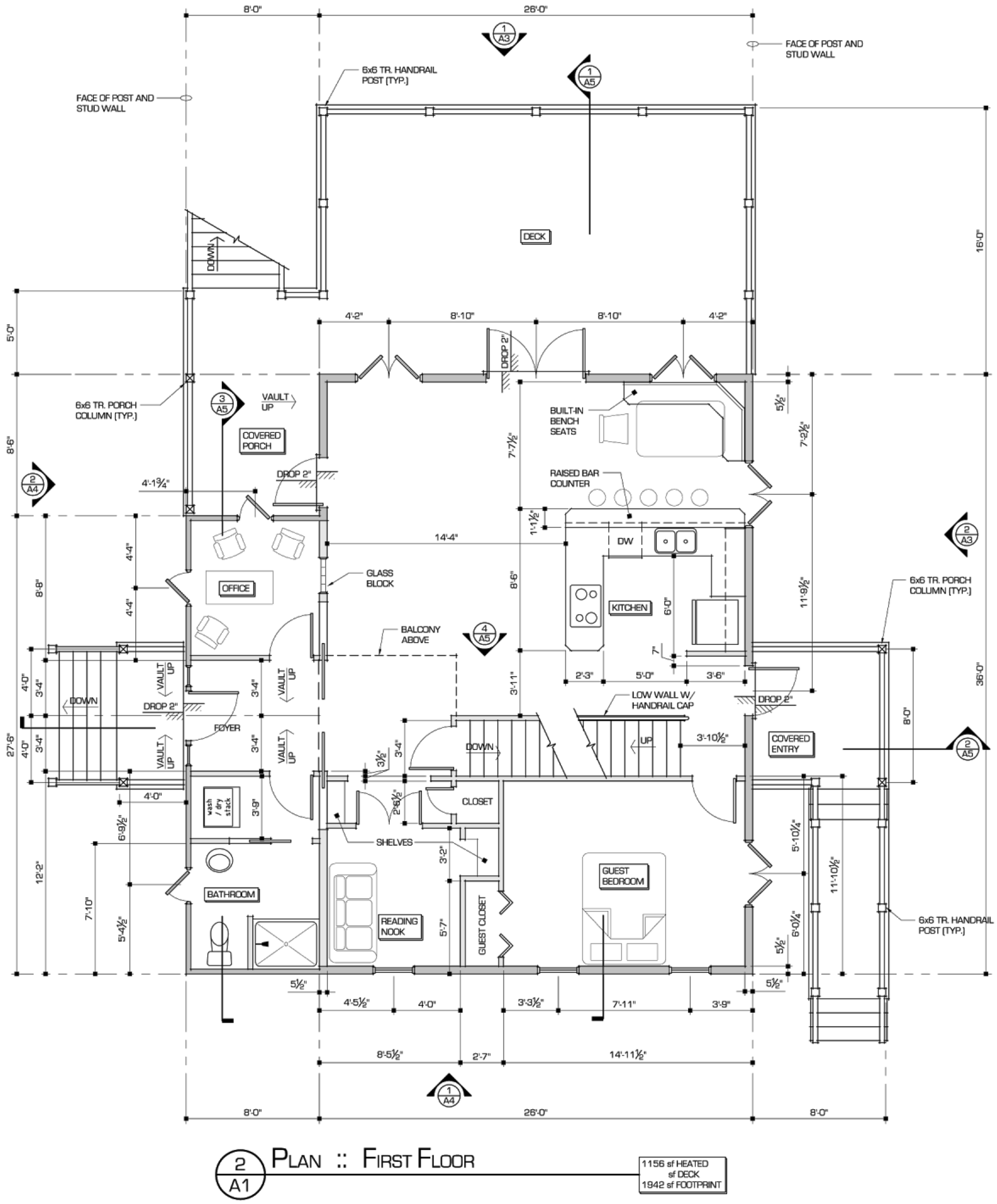


Figure 2: Tapscott Cottage - First Floor Plan

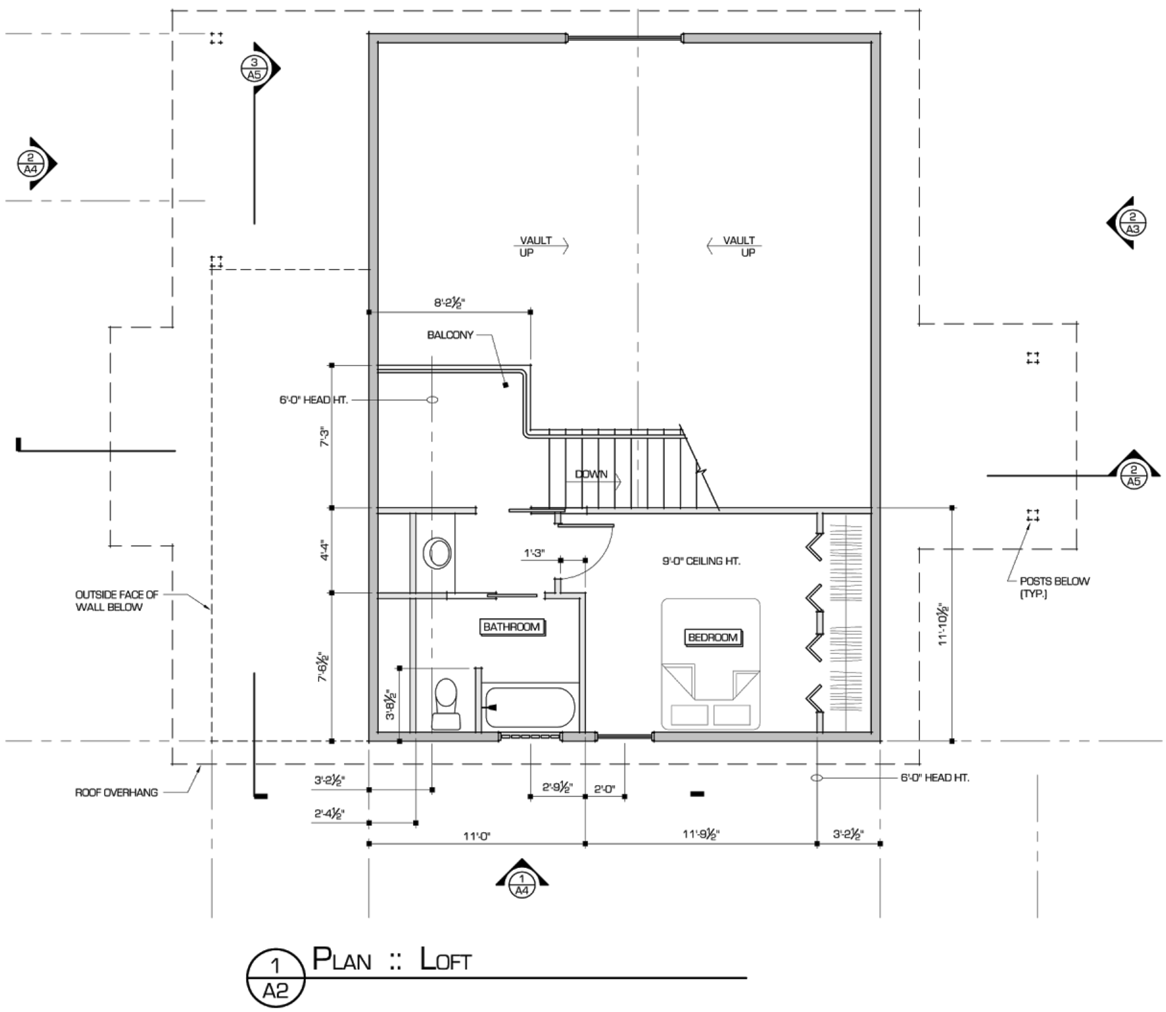


Figure 3: Tapscott Cottage - Loft Floor Plan

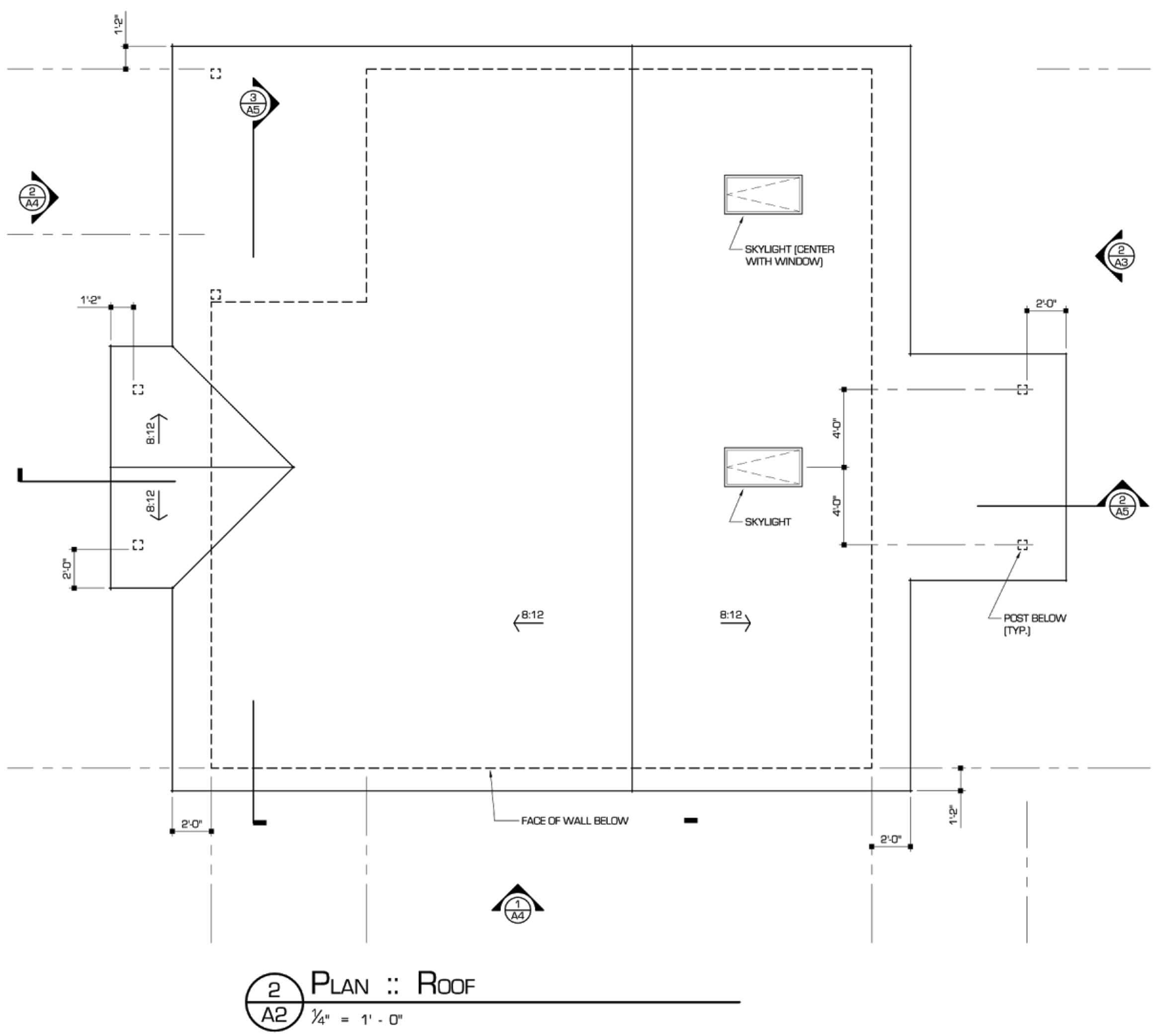


Figure 4: Tapscott Cottage - Roof Plan

2 A3 ELEVATION :: SIDE

1 A3 ELEVATION :: RIVER VIEW

Figure 5: Tapscott Cottage - Elevations

2 A4 ELEVATION :: SIDE (main entrance)

1 A4 ELEVATION :: FRONT

Figure 6: Tapscott Cottage - Elevations

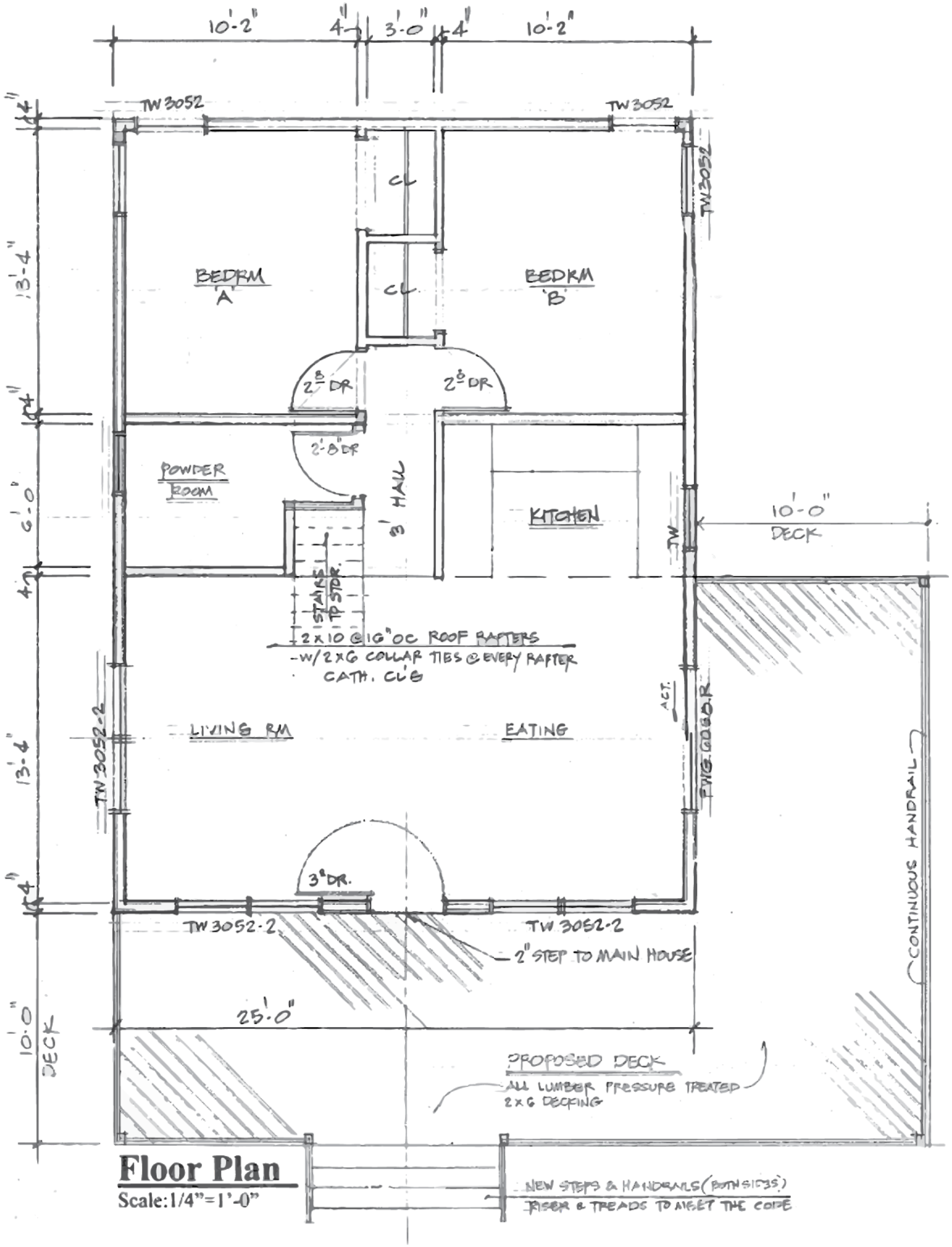


Figure 7: Slockett Cottage - Ground Floor Plan

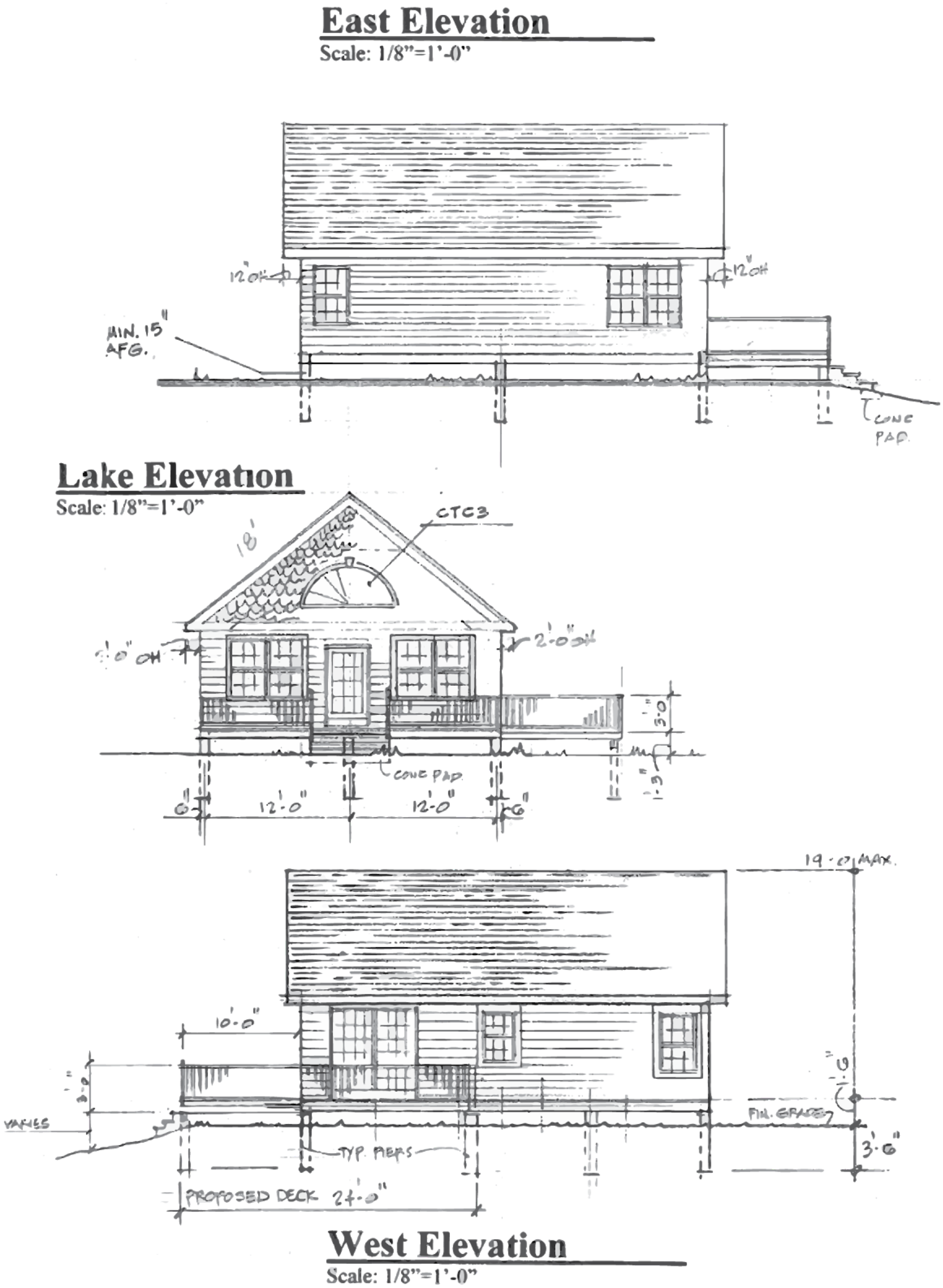


Figure 8: Slockett Cottage - Elevations

Figure 9: Cedar View Cabin - Perspectives

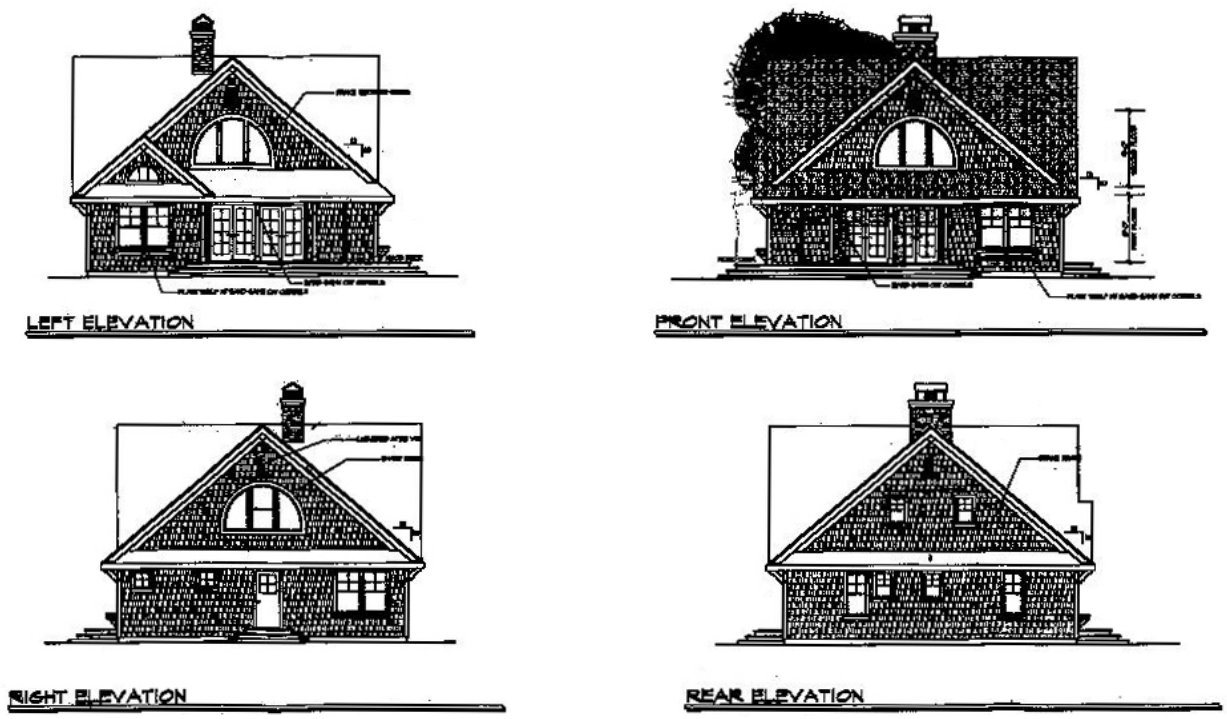
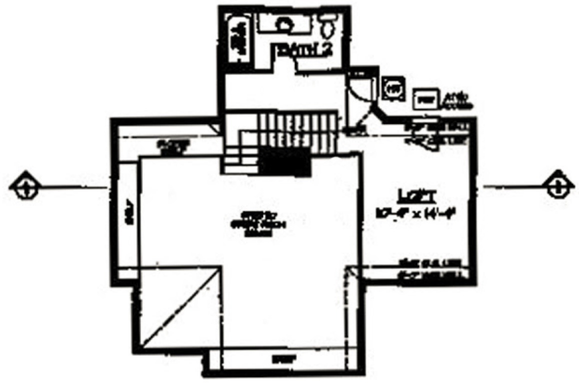
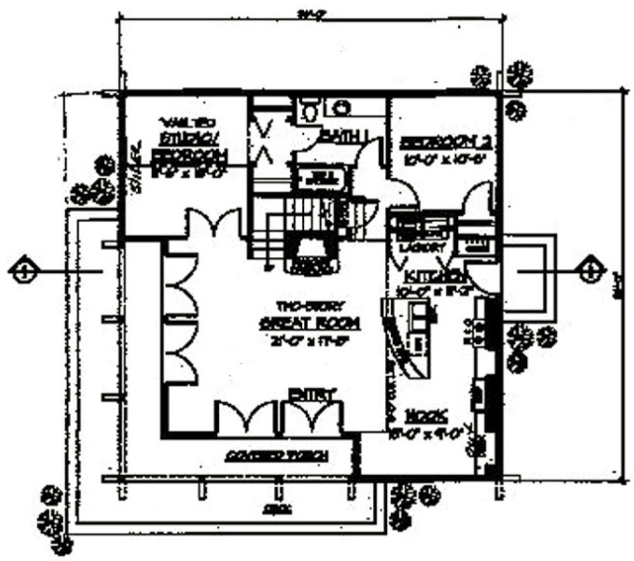


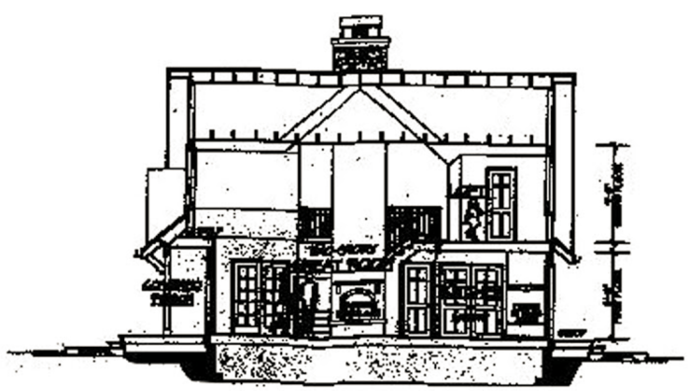
Figure 10: Cedar View Cabin - Elevations



Second Story Floor Plan



Ground Floor Plan



Building Section

Figure 11: Cedar View Cabin - Floor Plans and Section

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