Adaptations of Cementitious Structural Insulated Panels for Multistory Construction

A report by THE FEDERATION OF AMERICAN SCIENTISTS

for THE CHARLES PANKOW FOUNDATION

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FAS

CHARLES PANKOW
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Building Innovation through Research

Letter from Federation of American Scientists President, Henry Kelly

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The building industry has managed to dodge the innovation in materials, design, assembly methods, and quality control management that has revolutionized most other manufacturing businesses in the United States. Automobiles are expected to use advanced composites to increase safety and performance, and we are used to the idea that there are more than 50 microprocessors in a car controlling everything from the windows to fuel injection. But there's very little on a modern construction site that would surprise your grandfather.

The sluggish rate of innovation in construction makes it difficult to imagine how we can provide safe, comfortable, affordable housing for the seven billion people on the globe without placing unacceptable burdens on world resources. Comfort and safety are basic essentials in a good life, which should be reflected in our homes and work. However, at least a third of the world's population still lives in primitive conditions—two billion people have little or no electricity.

Wars, earthquakes, floods, and other calamities create new housing demands and often lead to enormous camps where displaced persons are forced to live in primitive structures for years. Often tents are the only affordable shelter. Despite our position as a global leader, the United States is scarcely an exception. The victims of the Katrina and Rita hurricanes are still cramped into unhealthy travel trailers two years later as states try to provide acceptable temporary and permanent shelter for them. Unfortunately, the technological innovation that has led to productivity, growth, and cost reduction in other manufactured products has not had a similar impact on housing, and these problems continue to grow.

Secondly, construction quality has an enormous influence on safety when buildings face strong winds, earthquakes, and fires. Millions of people in Turkey, Iran, Afghanistan, Pakistan, and neighboring countries live in structures that will collapse in a major earthquake. And again, the United States is not exempt from this problem, as many areas, including much of California, the central Mississippi River Valley, and Charleston, South Carolina, are in high-risk earthquake zones. In addition, a large fraction of the world's population lives in coastal cities that face huge risks from hurricanes and typhoons. In the United States, there's been a dangerous collision between coastal cities and an insurance industry increasingly adverse to underwriting structures exposed to hurricanes. Technology and quality control management can provide much greater safety while lowering costs. With structural insecurity spread throughout the global building stock, the building industry needs to adapt to address these dangerous realities.

Finally, the quality of construction has an enormous impact on world use of resources and energy, with a corresponding impact on global climate change. In the United States, buildings use nearly 70 percent of electricity. While developing countries typically use much more electricity in industry, they move rapidly toward excessive U.S. consumption patterns as their wealth grows. Energy use is skyrocketing as the population moves to urban areas from rural areas where wood and other biomass is still used to produce more than half of heating and cooking. According to recent Lawrence Berkeley Lab studies, energy used for air conditioning, refrigerators, lighting, and other building energy use represents more than a quarter of all energy use in China and electricity use in buildings. Building demand for electricity is increasing at twice the national rate of electric demand. Rapid construction of residential and commercial structures is driving the enormous increases in demand for cement and steel—which dominates Chinese industrial energy use. Few of these new buildings provide adequate insulation or meet China's own standards for efficient appliances. Turkey has had an almost identical experience, although it is growing at a less spectacular rate. Here again, technology should allow homes and commercial buildings to operate at enormously reduced levels of energy use, and new materials should drive down the energy costs of construction.

There are good reasons to believe that construction can benefit from the advances that have driven huge increases in quality and cuts in cost in other industries—improvements driven by sophisticated understanding of materials, advanced computer controlled design and testing, and management methods that provide quality at all stages of production. This research presents one of those promising opportunities. While seemingly unspectacular, these types of advances in the field of construction turn out to be essential for meeting our hopes for a secure and sustainable future economy.

Dr. Henry Kelly

Abstract

This document details the procedures for designing and constructing cementitious structural insulated panels (CSIPs) elements in multi-story buildings as curtain wall assemblies. A general discussion of the history of sandwich panels, the engineering mechanics of sandwich panels, and the application of sandwich panels in construction are presented. The application of CSIPs including the constructability, the optimization of CSIP details for energy efficiency, and general code limitations to CSTIP application in multistory construction is discussed. Finally, a method for engineers to adopt in applying CSIPs to multistory buildings is presented. The material, data, and appendixes are presented in detail that a knowledgeable engineer can immediately work with manufacturers of CSIPs to replicate the design and construction methods and principles described herein as the sole source of technical information for deployment of CSIPs in multistory construction.

Acknowledgments

We would like to express great appreciation for Dr. Robert Tener's dedication, diligence, and patience at pulling together this innovative research. We'd also like to thank Charles Pankow Foundation for funding a project which will no doubt start and expand an industry which has been thus far limited to residential construction. We'd also like to acknowledge the following partners for helping contribute to this report:

- Khalid Mosalem (UC Berkeley)
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0 – Project Introduction

0.1 – Scope of Work

The research partnership between the Charles Pankow Foundation and the Federation of American Scientists (FAS) allowed FAS to leverage completed and ongoing research to evaluate the potential of a specific type of Structural Insulated Panels (SIPs), Cementitious Structural Insulated Panels (CSIPs),in multistory buildings. While the term “multistory” does not signify a definitive height limit, the performance and design of panels, as well as current restrictions in the relevant building codes, limit the height. Thus, within this report, the term “multistory” refers to buildings with more than three stories, which is the current limitation for SIP construction per code. This limitation is a significant and defining factor for this research and the industry’s growth and development.

This report documents the results of this research project, including the implementing design procedures and appropriate certification the design procedures are suitable for adoption and use in building design and construction practice. It also includes the final Dissemination Plan, detailing the action steps and schedule for implementing this plan.

Manufacturers need to be recruited to work together to institute the research encapsulated in this report as a consensus industry standard.

0.2 – Goals & Objectives

The initial FAS test projects with CSIPs all involve housing of fewer than three stories. This work raises the following question: Can CSIPs provide high-quality performance characteristics for multistory structures while simultaneously reducing constructing times, construction costs, and operating costs? FAS evaluated a variety of design options for multistory buildings regarding their structural strength, energy efficiency, earthquake and hurricane durability, and cost. The key technical question is whether the buildings can be designed to exploit CSIPs’ unique structural strength, energy efficiency, and other features, and how CSIPs can be applied to multistory construction—either as load-bearing elements, in-fill panels, curtain walls, or a combination of the three.

This project will provide the research and technical information that the building industry needs to evaluate the potential contribution of CSIPs in response to its growing interest in advanced building solutions.

0.3 – Benefit to the Industry

When this research first began, FAS leveraged the existing pool of certified CSIP companies to obtain information, test reports, and certifications. At the same time, FAS began investigating the codes and code certification process for these new materials. FAS soon discovered the existing industry had significant shortcomings in the code reports obtained to date. In that effort, we began discussing issues in the industry and inciting manufacturers of fiber-cement boards (primarily manufactured using the

Hatcheck method) to start testing CSIPs with industry partners like the Structural Insulated Panel Association (SIPA).

This research has paid off as new manufacturers are entering the market with CSIP products. In the course of this work, FAS began to understand and address how CSIPs can be applied to multistory construction using sound scientific data. Likewise, FAS began to understand, unlike precast concrete wall panels, the performance of composite sandwich panels with predominately expanded polystyrene (EPS) cores need validation from physical testing and cannot solely be relied upon by simple engineering mechanics because of the varieties of glues, core materials, and inconsistent results from the lamination process. The manufacturing of SIPs has not been a rigorously scientific endeavor, and more research and development of standards and processes is needed to move the industry toward a more uniform commodity. However, respected strides in this area the CSIP industry can leverage include the American National Standards Institute (ANSI) process SIPA is undertaking and the efforts to get the International Residential Code (IRC) to recognize wood SIP walls.

The two most significant contributions of this report are:

1) Envisioning how to grow CSIPs and composite panels into more sophisticated markets like multistory construction (and commercial construction) and
2) Developing a process tree to help engineers, architects, owners, and consumers choose a candidate system to apply in buildings.

First, the images and examples used in this document should help illustrate to the industry the intrinsic value in adapting commercial construction techniques to the SIP industry to grow new markets. And second, clear logic is needed to navigate the complex web of codes and manufacturer claims to determine what systems are good candidates to be leveraged to meet these new uses.

This document's purpose is to guide engineers, architects, and owners in adapting CSIPs to multistory buildings. However, it will be equally useful for the CSIP manufacturers so they can understand what is needed from their operations. It should also be a roadmap for the CSIP industry, which is slowly maturing, to compete not only against wood but also against commercial systems to see new markets and new market growth numbers.

To ensure this information is relevant, accurate, and complete, FAS, with the guidance and assistance of the Pankow Foundation, worked with the Architectural Engineering Institute of the American Society of Civil Engineers to form an Industry Advisory Panel (IAP) for the project. The IAP played a key role in advising FAS on the information most beneficial to the building industry. IAP members included:

- Dr. Mohammed Ettouney, Principal, Weidlinger Associates
- Dr. Christian Meyer, Professor of Civil Engineering, Columbia University Fu Foundation School of Engineering and Applied Science
- Dr. Michael Mazor, Building Scientist for New Product and Business Development, Dow Building Solutions

In addition, many industry professionals have reviewed and contributed to this document.

0.4 – About the Federation of American Scientists

The FAS is a nonprofit organization founded in 1945 by members of the Manhattan Project, who were concerned about the implications of the atomic bomb for the future of humankind. Endorsed by sixty-eight Nobel Laureates in chemistry, economics, medicine, and physics, FAS addresses a broad spectrum of issues in carrying out its mission to promote humanitarian uses of science and technology.

0.4.1 – About the Building Technologies Program

Beneath its ideological umbrella, FAS's Building Technologies Program works to mitigate climate change and advance social justice and environmental responsibility through the building industry. Buildings are the leading consumer of electricity and energy in our country, and energy production and use are responsible for the vast majority of human greenhouse gas emissions. With this in mind, the main focus of FAS's work is to improve energy efficiency without sacrificing affordability, safety, and performance. FAS has focused on developing technologies that are affordable, efficient, and obtainable by all socioeconomic classes. To guide these efforts, FAS is directing its current and future research in the following areas:

1. Policy: working to create guidelines, evaluation systems, and incentives to improve energy efficiency standards and to reduce the environmental impact of the built environment on a national and international scale.

2. New Technologies: developing new technologies that improve the energy efficiency and reduce the environmental impact of the built environment, as well as providing for their practical implementation.

3. Training: developing training programs to teach building inspectors about energy efficiency standards, energy audits, and advanced building systems. This training helps ensure inspectors can properly measure and implement energy incentives and evaluate advanced building systems.

4. Affordable Housing: applying energy-efficient, environmentally responsible technologies to affordable housing projects through demonstration projects, working with affordable housing groups, and developing appropriate building systems at prices comparable to traditional systems.

5. Emergency Housing: providing economically viable, energy-efficient, environmentally responsible housing stock for emergency relief in temporary and intermediate time frames.

6. Demonstrations: constructing demonstration buildings to show the potential of these technologies and advanced building systems on a local scale. FAS partners with charitable organizations, such as Habitat for Humanity, to build energy-efficient, affordable housing, while simultaneously allowing for real-time monitoring of new building systems.

FAS works to create strategically optimized solutions within these categories through academic, professional, and industry partnerships to positively affect the global impact of our built environment.

0.5 – Key Individuals

Henry Kelly, Ph.D., has been president of the FAS since July 2001. Prior to joining the FAS, Dr. Kelly spent more than seven years as Assistant Director for Technology in the Office of Science and Technology in the White House. There, he helped negotiate and implement administration research partnerships in energy and the environment, information technology, and learning technology. These partnerships included new automobile and truck technology, housing technology, bioprocessing technology, and information technology.

Before his tenure at the White House, he served as a senior associate at the Congressional Office of Technology Assessment, an assistant director for the Solar Energy Research Institute, as a staff member of the U.S. Arms Control and Disarmament Agency. Dr. Kelly is an elected fellow of the American Physical Society, the 2002 winner of the APS' Leo Szilard Lectureship Award for promoting the use of physics for the benefit of society, and named the 2000 Champion of Energy Efficiency by the American Council for an Energy-Efficient Economy. He is the author of numerous books and articles on science and technology policy issues. Dr. Kelly received a PhD in physics from Harvard University.

Joseph Hagerman is the project manager of the FAS's Building Technologies Program in Washington, D.C. As project manager, Mr. Hagerman researches new building technologies while demonstrating these technologies in the public sector. Mr. Hagerman graduated from Mississippi State University in 2001 with a Bachelor's degree in Architecture. In 2006, Mr. Hagerman completed a Master's of Science degree in Civil Engineering at Columbia University's Fu Foundation School of Engineering and Applied Science. His academic work focused on engineering mechanics and construction technology. While at Columbia, Mr. Hagerman interned with Steven Winter Associates, Inc. in Norwalk, Connecticut, specializing in building systems consulting. In 2005, Mr. Hagerman won the Metropolis Next Generation® Design prize for developing a manufacturing strategy to cost effectively deliver bioremediating plant material inside open cell interlocking concrete pavers, called "biopavers." He was also awarded the 2005 Rafael Viñoly Fellowship, giving him the opportunity to conduct architectural-based research with Rafael Viñoly Architects PC, an internationally renowned design firm.

Brian Doherty is a research assistant on FAS's Building Technologies Program. He joined FAS in June 2007 after completing his Bachelor's degree in the Growth and Structure of Cities with a concentration in Architecture at Haverford College in Haverford, Pennsylvania. Prior to joining FAS, Mr. Doherty held internship positions at multiple architecture firms, including TLB Architecture and the 1998 AIA Architecture Firm of the Year, Centerbrook Architects and Planners, LLC.

John Millhone is Advisor to the FAS's Building Technologies Program. Before joining FAS, Mr. Millhone held an array of positions at the Department of Energy (DOE) until he retired as the Director of the Office of Weatherization and Intergovernmental Programs (OWIP) on December 31, 2003. As the Office Director, Mr. Millhone managed a $330 million annual budget to deploy energy-saving and renewable energy technologies to advance U.S. strategic policy and economic, environmental, and social objectives. Mr. Millhone also directed DOE's participation in a multi-agency project to build international Climate Change program capacity and to demonstrate the environmental, political, and economic benefits of bilateral greenhouse gas emission-reduction projects. Mr. Millhone served as the Chairman of the Energy Efficiency Committee of the United States Energy Association and the Chairman of the End-Use Working Party of the International Energy Agency. In 2004, the DOE awarded Mr. Millhone its Distinguished Career Service Award.

Zeynep Gueven worked as a research assistant for the FAS's Building Technologies Program until June 2007. She joined the FAS in December 2004, after completing her Bachelor's degree in international affairs and media and public communication at the George Washington University in Washington, D.C. Prior to joining FAS, Ms. Gueven interned with the United Nations Office on Drugs and Crime in Vienna, Austria, the American-Turkish Council, America Abroad Media, and the Turkish Embassy in Washington, D.C.

Todd Gerarden is a mechanical engineering student at the University of Virginia's School of Engineering and Applied Science. He is a member of the FAS's Policy Internship Program, applying his academic experience in structural mechanics to both policy- and industry-oriented projects.

1 – About SIPs and CSIPs

This report focuses on a relatively new technology and a relatively small industry within the larger scope of the building community. In addition, by addressing cementitious-faced SIPs, this report addresses an even narrower segment.

To put this report in perspective, we first review the current status and practices of the SIP industry.

1.1 – What are SIPs and CSIPs?

SIPs are high-performance composite building panels used in floors, walls, and roofs for residential and light commercial buildings. These panels are fabricated in a factory and shipped to a construction site, where they can be quickly assembled to form a tight, energy-efficient building envelope.

Figure 1 – Structural Insulated Panel with Cement Fiber Facing

SIPs are a simple composite sandwich panel. ASTM International defines simple sandwich panels as "a three layered construction formed by bonding a thin layer (facing) to each side of a thick layer (core)."[1] The term "composite" refers to any material in which two or more distinct materials are combined together, yet remain uniquely identifiable in the mix.

Generally, SIPs are made by sandwiching a core of rigid foam plastic insulation between two structural skins, though many different variations (based on facing and core materials) are included in the blanket definition. SIPs are currently made with a variety of structural skin materials, including oriented strand board (OSB), treated plywood, fiber-cement board (cementitious), and metal. However, virtually any bondable material could be used as a facing. Core materials are typically expanded polystrene (EPS), extruded polystrene (XPS), or polyurethane, but other rigid insulation can be used as well. Facings and core materials are bonded by structural adhesives.

These variables allow for panels to be optimized to the specific needs of any project. SIPs are typically available in thicknesses ranging from 4½ inches to 12¼ inches. Walls are commonly between 4 and 6 inches, and roof panels are generally thicker (often up to 12 inches, depending on climate

[1] ASTM C274 - 07 Standard Terminology of Structural Sandwich Constructions

conditions). SIPs with cementitious facings are typically cut to 4 feet by 8 feet. SIPs may be as large as 9 feet by 28 feet with OSB facings. Custom sizes are also available, and many manufacturers offer curved SIPs for curved roof applications.[2]

This design flexibility, as well as the different combinations of core and facing materials, allow for unique performance properties for each project. SIPs' flexibility, strength, and energy performance make them an important twenty-first-century building material for high-performance buildings.

NOTE: *As a designed composite, SIPs are an assembled product. Therefore, the subcomponents and assemblies must be tested rather than evaluated theoretically.*

Figure 2 - Diagram of SIP House Construction with OSB Facings

1.2 – A History of SIPs

SIPs were developed nearly 75 years ago when the Forest Products Laboratory (FPL), established by the U.S. Department of Agriculture, built the first SIP house in 1935 in Madison, Wisconsin. FPL engineers speculated that plywood and hardboard sheathing could take a portion of the structural load in wall applications. Their prototype SIPs were constructed using framing members within the panel combined with structural sheathing and insulation. These panels were used to construct test homes, which were continually tested and monitored for the next 31 years.[3]

Following the FPL experiment, Alden B. Dow, son of the founder of Dow Chemical Company and a student of Frank Lloyd Wright, created the first foam core SIP in 1952. By the 1960s, rigid foam insulating products were readily available, leading to the production of SIPs as they are today.

In the early 1990s, advanced computer-aided manufacturing (CAM) technology was developed. This technology can convert computer-aided design (CAD) drawings to code and allow automated cutting machines to fabricate SIPs to match a building's specific design. CAD-to-CAM technology has streamlined the SIP manufacturing process, bringing further labor savings to builders.

[2] "Structural Insulated Panels Product Guide". SIPA and APA. December 2007.
[3] "The History of SIPs", http://www.sips.org/

This development coincided with SIPA's formation in 1990. SIPA was formed to provide support and visibility for those manufacturing and building with this emerging building technology and to increase SIPs' market share through a partnership with the Engineered Wood Association (APA).

Taking advantage of the building industry's growing interest in energy efficiency, SIPA collaborated with the Partnership for Advanced Housing Technology to "develop a set of prescriptive performance standards, which were submitted for inclusion in the International Code Council's Residential Code (IRC)."[4] On May 22, 2007, structural insulated panel wall systems were adopted into the IRC. Section R614 of the 2007 IRC Supplement and subsequent editions of the code include prescriptive standards for SIP wall construction. The IRC Prescriptive Method for SIPs is attached as Appendix A. For more information regarding the adoption of SIPs in building codes, as well as how this changes the design decision process, see section 2.2.

Today, SIPs offer a high-tech solution for residential and low-rise nonresidential buildings, with a great potential for multistory building applications.

1.3 – Current Material Options in the SIP Industry

A closer examination of SIP's three components—the structural facing, insulating core, and adhesive holding the pieces together—yields a greater understanding of their potential. The variety of available materials allows panels to be tailored to each project and component materials to complement each other, making the design of SIPs both a material selection problem and a dimensional problem. For example, increasing the core thickness to obtain the proper design values can compensate for facing materials that lack rigidity. This flexibility allows materials to be chosen for reasons other than mechanical performance.

The rapid development of new technologies makes for new possibilities, and the material options are essentially boundless. Thus, this review cannot touch on every available option. Instead, it includes the most common and readily available material options currently used in the SIP industry and highlights the material options focused upon in this research.

1.3.1 – Facing Materials

Ideally, SIP facings should have high stiffness (high flexural rigidity), high tensile and compressive strength, high impact resistance, quality surface finish, resistance to environmental impacts (e.g., chemical, UV, heat, etc.), and durability.[5]

The following table reviews the most common facing materials in the current SIP market, examining their positive and negative performance attributes.

[4] Get Energy Smart.org "What Are SIPs?"<http://www.getenergysmart.org/Files/Presentations/HY-R%20NYSERDA%20Presentation.ppt> 8 Nov. 2006

[5] Zenkert, D. "The Handbook of Sandwich Construction". Pg. 12.

Common SIP Facing Materials		
Material	Pros	Cons
Oriented Strand Board	• Inexpensive • Readily available • Recognized in current IRC code	• Requires finishing on interior and exterior • Swells with moisture
Cement Fiber	• Will not rot, burn, or corrode • Acts as a finished interior and exterior • More durable and lasts longer	• Heavier than other options and more difficult to handle • Brittle and prone to cracking during shipment • More expensive than OSB
Metal	• Inexpensive • Readily available • More durable and lasts longer	• Requires finishing on interior and exterior
Others	Magnesium oxide board, fiber-reinforced polymers	

Table 1 – Common SIP Facing Materials

OSB facings are used for the vast majority of SIPs. OSB is an engineered wood product made from cross-oriented layers of thin, rectangular wooden strips compressed and bonded together with wax and resin adhesives. OSB has been extensively tested as a load-bearing material and is commonly available in large sizes. In addition, the Prescriptive Method Supplement to the IRC (discussed in the next chapter) requires OSB facings for SIPs to be recognized in the code for one- to two-story residential buildings.

Metal SIP manufacturers often use aluminum as a skin material. This structural panel system is used in both residential sites, such as carports or walkways, as well as industrial systems, such as the construction of cold storage facilities. Panel designers sometimes take advantage of their aluminum siding and connect panels metal to metal with pop rivets. Another option is a cam-lock system or a system in which internal gutters allow the panels to be reversed.

Fiber-cement board faced SIPs, referred to as CSIPs, are the focus of this research. CSIPs constitute a smaller portion of the market than OSB faced SIPs, but they carry many added benefits. CSIPs are typically manufactured from cellulose-reinforced cement boards for inside and outside skins, commonly referred to as “fiber-reinforced cement,” or simply “fiber cement.” Table 2 – Required Evaluation of Cement Fiber Panels” lists required testing.

Fiber-cement panels can have different finished looks, such as a wood grain, stucco, or smooth.[6] This removes the need for CSIPs to be finished on the interior or exterior, making it the entire wall assembly

[6] http://www.toolbase.org/Building-Systems/Whole-House-Systems/fiber-cement-faced-sips

and removing the need for several steps in the construction process. If CSIPs are used as the interior finish surface, they must comply with the appropriate fire codes. Where used as the exterior finish surface, fiber-cement board must be tested for weather resistance, transverse and racking loading, and fire resistance.

In addition to providing an interior and exterior finish, buildings constructed with CSIPs typically will last longer and require less maintenance than those built with other types of SIPs. Fiber cement boards have a high resistance to moisture absorption, will not support black mold growth, and are rot and vermin resistant. CSIPs have a higher fire rating than OSB-faced SIPs, and in most residential applications, no drywall is necessary. This lack or drywall requirements is determined by the fire-requirements of the applicable building code. See Section 2.2.8 for a more detailed discussion of fire code requirements and limitations of CSIPs.

While there are many benefits to CSIPs, there are negative aspects as well. CSIPs are significantly heavier than OSB SIPs. A 4’x8’ CSIP panel weighs roughly 180 lbs., while a 4’x8’ OSB SIP weighs 111 lbs. This makes CSIPs more cumbersome during construction. In addition, due to the free silica—a health hazard if inhaled—contained in most cement fiber, in-field modifications (especially with rotary saws) should be avoided.

The final difficulty with CSIPs is the relative infancy of the industry. Since few CSIP manufacturers and large-scale organizations exist, CSIP prices are higher for the consumer than need be, and service is less reliable and consistent.

Required Evaluation of Cement Fiber Panels	
Interior Use	• ASTM C1325 – Standard Specification for Non-Asbestos Fiber-Mat Reinforced Cementitious Backer Units
Non-Structural Use	• ASTM C1325 with Section S1 • ICC-ES AC376 – Acceptance Criteria for Reinforced Cementitious Sheets Used As Wall Sheathing and Floor Underlayment
Interior Finish	• ASTM E84 – Standard Test Method for Surface Burning Characteristics of Building Materials. *Refer to Section 2.2.8 for more information on this testing.*
Construction Types	• ASTM E 119 – Standard Test Methods for Fire Tests of Building Construction Materials • IBC Table 601.
Non-Combustible	• ASTM E136 – Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C
Vertical Use	• ICC-ES AC 376
Racking Strength	• ICC-ES AC 376 • Section 3.6/AC269 – Acceptance Criteria for Racking Shear Evaluation of Proprietary Sheathing Materials Used as Braced Wall Panels
Water Resistive Barrier	• Assembly Tests per ASTM E331 – Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference *under the conditions specified in* IBC 1403.2. • Tests on lateral resistance and nail head pull through shall be conducted with ASTM D1037 – Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials
Diaphragm Strength	• ICC-ES AC 376

Table 2 – Required Evaluation of Cement Fiber Panels

1.3.2 – Core Materials

The core is responsible for providing thermal insulation, counteracting shear and transverse forces and resisting moisture penetration. The insulating core also reduces the panel's weight (compared to some other prefabricated structural panel systems), making CSIPs easier to construct and better suited for seismic-active regions.

The properties of primary interest for core materials are density, shear modulus, shear stiffness, stiffness perpendicular to the faces, thermal insulation, and acoustic insulation.[7] The following tables describe the relevant performance of the most common core materials in the current SIP market.

Minimum Properties for SIP Insulating Core Materials			
Insulation Material	Type I EPS	Type X XPS	Polyurethane
Min. Density, lb./ft.^{3}	0.9	1.30	2.2
Thermal resistance of 1.00 in. thickness, minimum °F-ft.^{2}h/Btu at mean temperature: 40°F	4.0	5.4	6.7
Thermal resistance of 1.00 in. thickness, minimum °F-ft.^{2}h/Btu at mean temperature 75°F (23.9°C)	3.6	5.0	X
Compressive resistance at yield or 10% deformation, whichever occurs first (with skins intact), minimum	10.0	15.0	19
Flexural strength, minimum, psi	25.0	40.0	30
Water vapor permeance of 1.00 in. thickness, maximum, perm (ng/Pa-s-m^2)	5.0	1.1	2.3
Water absorption by total immersion, maximum, volume %	4	0.3	4.3
Dimensional stability, (change in dimensions), maximum, %	2	2	2
Tensile strength, minimum (ASTM D 1623), psi	X	X	35
Shear strength, minimum (ASTM C 273), psi	X	X	25

X = Please reference manufacturer's data

Table 3 – Minimum Properties for SIP Insulating Core Materials[8]

Expanded Polystyrene (EPS) is the most common core material, used in 85% of all SIPs.[9] EPS has a closed-cell, moisture-resistant structure composed of millions of tiny air-filled pockets. It generally does not release ozone-depleting chlorofluorocarbons (CFCs). The material is molded into large blocks and cut to the proper shapes for use in SIPs.

[7] Zenkert, pg. 23.
[8] This chart was compiled using a list of minimum values for each material, taken from ASTM C 578, ASTM D 1622, ASTM D 1621, ASTM C 203, ASTM D 1623, ASTM C 273, ASTM E96, ASTM C 27, and ASTM D 2126.
[9] Morley, Michael. Building With Structural Insulated Panels. Pg. 23.

The IRC Prescriptive Method requires that SIPs use molded EPS as a core material. This EPS must meet the requirements of ASTM C 578 (referenced in “Minimum Properties for SIP Insulating Core Materials”), a consensus document developed by producers of polystyrene foam, third-party testing companies, regulatory agencies, and insulation users in North America. It covers the types, physical properties, and dimensions of cellular polystyrene used as thermal insulation for temperatures from -65°F to 165°F. Flame spread rating of SIP cores must be less than 75 and the smoke-development rating shall be less than 450, as tested in accordance with ASTM E 84. This does not mean all SIPs must use EPS, but if another material is used, it must be shown to be of equal or better performance by a professional engineer.

Extruded Polystyrene (XPS) is similar to EPS, but is not used nearly as frequently within the SIP industry. XPS performs almost twice as well as EPS in regards to compressive strength, flexural strength, and shear resistance. However, these benefits come at a significant cost: sheets of XPS are far more expensive, can only be made four inches thick, and do not create a perfectly flat gluing surface. Because of these drawbacks, XPS is used infrequently in the SIP industry.

Polyurethane or polyisocyanurate (both commonly referred to as urethane) is also used by manufacturers as an insulating material. Liquid foam is injected between two skins under considerable pressure, which hardens to produce a strong bond between the foam core and the skins. The foam core contains a blowing agent, some of which escapes over time, reducing the initial R-value of the SIP from about R-9 to R-7 per inch (2.5 cm) of thickness. Wall panels made of polyisocyanurate or polyurethane are typically 3.5 inches (89 mm) thick. Ceiling panels are up to 7.5 inches (190 mm) thick. These panels, although more expensive, are more fire-resistant and water vapor-diffusion-resistant than EPS.[10]

1.3.3 – Adhesives

The final component of a SIP assembly is the adhesive that bonds the facing and core materials. As with facing and core materials, there are several options for adhesive. No matter which option is chosen, this glue must:

- Resist Forces: The adhesive joint must be able to transfer the design loads (have the desired tensile and shear strength). They must resist buckling and racking forces.
- Thermal stresses: A frequent cause of debonding (and catastrophic failure of the panel) is due to thermal stress.
- Moisture Penetration: The adhesive must be able to withstand any sort of moisture penetration into the joint without delamination or bond failure.

Other variables of adhesive performance that must be considered include preparation requirements for application, required bonding pressure, adhesive viscosity, bond thickness, viscoelastic properties, and curing shrinkage.

[10] http://www.eere.energy.gov/

Defining the common performance properties of available adhesives is difficult because each is a proprietary material. However, any adhesive used in the construction of a SIP must comply with International Code Council Acceptance Criteria AC05.

1.4 – Factory Fabrication

SIPs and CSIPs are prefabricated under factory-controlled settings prior to use on a building site. The only code requirement for SIP fabrication is that the process must conform to quality documentation in accordance with ICC Acceptance Criteria 10. Despite proprietary variations from manufacturer to manufacturer, the process is relatively similar throughout the industry.

Prior to SIP fabrication, shop drawings are created for the panels, detailing exactly how each panel will fit into the overall building design. A count of the required panels, their dimensions, and special cuts (such as windows and doors) is created, and each panel is made specifically for its purpose within the building.

Typically, fabricating EPS- and XPS-core SIPs begins by placing one facing out on the assembly area. The desired thickness of core material is run through a glue-spreading machine, where the appropriate amount of glue is spread on both sides of the core. The core section is then placed on top of the bottom facing, and a top facing is positioned above it. This assembly is moved into a press, which applies even pressure to the top and bottom facings. Specific adhesives require different pressure, curing time, temperature, and humidity, all of which are controlled.

After the panels are removed from the press, they are set aside to cure for 24 hours. Once cured, they are moved to the fabrication section of the plant, where windows, doors, electrical chases, and other openings specific to the project are prepared.

The approach to urethane panels is rather different. Panel facings are separated at the required distance by spacers, and the mixed components of the foam core are injected between the facings. As the foam expands and fills the void, the foam bonds the two facings together without the need for an adhesive.

1.4.1 – CSIP Plant Optimization

Although the manufacturing of CSIPs is typologically similar to wood SIP manufacturing, the plant should address the following key issues and concerns:

- Dust control: dust created by fiber cement contains free silica, which can result in silicosis if inhaled. Dust control for the fabrication and handling of FCB is critical.
- Smaller unit sizes: FCB comes in dimensions of 4’x8’, 4’x10’, and 4’x12’, while OSB ranges as high as 8’x24’.
- Higher weights per unit size: FCB is denser than OSB.
- Optimization of shop drawings to reduce fabrication.

Illustrated below is a 10,000 square foot SIP operation capable of producing roughly 1Mn square feet of panels per year (or roughly 250 to 300 affordable single-family homes per year). The capital costs in equipment are in the four SIP presses (roughly $25K each), the glue spreader (roughly $5K), the equipment to properly cut EPS to the desired size (roughly $5K), the vertical panel saw (roughly $5K) and the CNC machines (roughly $15K each). The total investment required is roughly $150K.

Basic CSIP Manufacturing and Fabricating

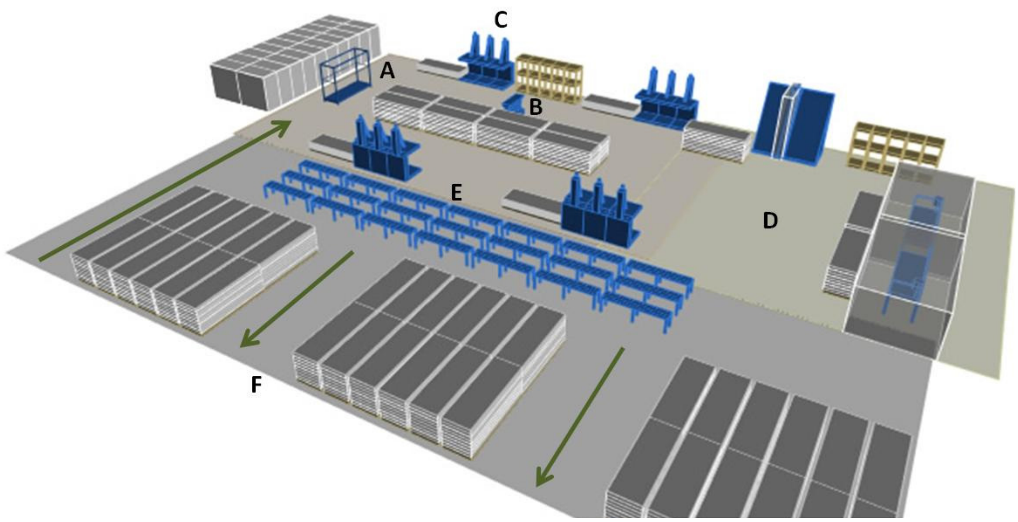


Figure 3 – Basic CSIP Manufacturing and Fabricating

This plant has three major zones: lamination (where the panels are laminated, denoted by A, B, C), basic fabrication (where the panels are cut, denoted by D), and final fabrication (where the panels are finished, labeled, organized, and shipped, denoted by E, F). These areas are outlined in the floor colors.

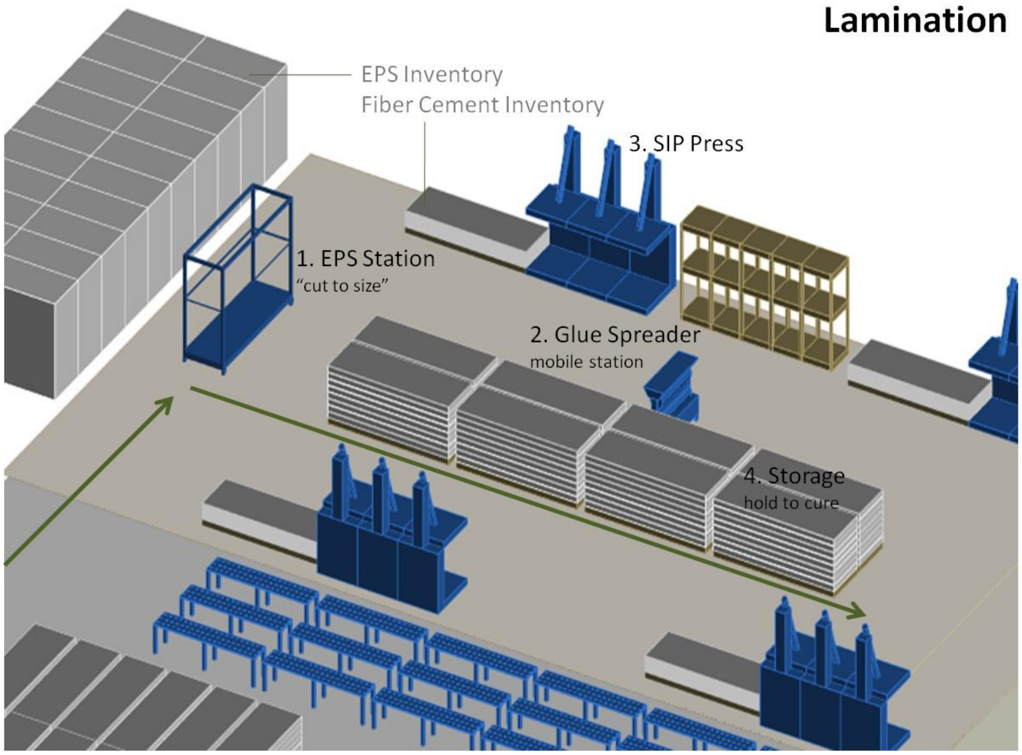


Figure 4 - Lamination

The process flow through the factory starts with the EPS station, where large blocks of EPS are inventoried and cut down to the desired panel size and thickness. Inventorying large blocks of foam is more cost-effective than inventorying various sizes of foam. This station's primary tool is a hot wire station (1) that can rapidly tool the foam. From this station, the foam is delivered to the individual panel presses (3).

The panel presses (3) are hydraulic presses that deliver a consistent amount of pressure to properly adhere the foam and the facing. Because the glue is exothermic and expansive, the press must offset this pressure. Large bundles of fiber-cement board, which by themselves are extremely heavy, are pre-positioned at the head of the presses to reduce time and fatigue. Additionally, the mobile glue spreader (2) is prepositioned near the press and foam to decrease travel distances. The presses should contain built-in pallets, so removing the CSIPs from the presses is a nominal task.

Figure 5 – Typical SIP Press

The presses are loaded by laying one sheet of FCB on the press from the co-located bundles, spreading glue on the foam using the co-located glue spreader, placing the foam on top of the FCB, and registering the final face of FCB on the foam. This sequence is repeated until the press is fully loaded. The hydraulic press is preloaded (to take up any slack) and the panels are re-registered to ensure they are uniform. The hydraulic press is set to the desired pressure and left for two to three hours or until the glue is fully cured. The crew then moves to the next press location. Four presses are shown in the Figure 5 – Typical SIP Press" for a total rate of 100 to 120 panels a day (three batches for four presses each). This process is a small batched process and is not continuous. After the presses are unloaded, the product may be held for 24hours to fully cure (4).

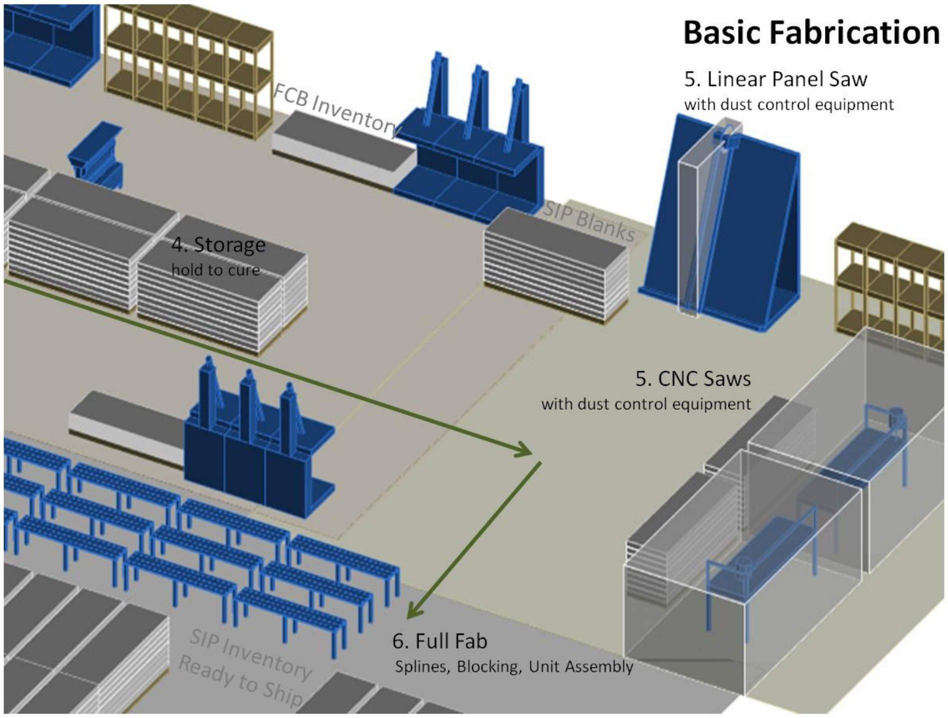


Figure 6 – Basic CSIP Fabrication

The next station is Basic Fabrication, where CSIP blanks (panels without any tooling) are cut to size or penetrations are cut out. These two tasks are the most critical in CSIP operations because they must be done with proper dust control. There are two primary cutting tools: (5) linear panel saws and CNC saws. The linear panel saw should be used when only one or two straight cuts are needed. A modified panel saw should be used with a blade capable of cutting a 6” panel. Next, for more complex cuts, a small CNC saw should be used with a tool capable of cutting through a 6” panel. These CNC saws are typically the lower end equipment (maximum of 4’x12’). Next the panels move to final or full fabrication, where the splines are cut, the panels are checked and labeled, and assemblies are cut, caulked, and primed (if allowed for). The rate by which basic fabrication runs is twelve panels per hour. Because many projects use blanks alone, this may or may not be the bottleneck and is the primary reason shop drawing optimization (to reduce cuts) is necessary.

At this stage, these panels flow on gravity conveyors to various stations.

Figure 7 - From Left to Right: Linear Panel Saw, CNC Saw, Gravity Conveyor

Staffing is based on the work team’s education. Lamination requires two operators and one shop hand; Basic fabrication requires two to three operators and one shop hand. A general manager is needed for the plant. Shop drawings can be done in-house, remotely by consultants, or outsourced. Therefore, a total of six operators, four shop hands, and one general manager are needed.

Once fabricated, SIPs are shipped to a job site, where they are erected per the building design. Section 1.5 describes the installation of SIPs, water barriers, and windows in their current applications. The information shows how these requirements can be addressed in high-rise applications. Those wishing to skip these details may turn to Section 1.6, The Current SIP Market, or Section 1.7, Current Limitations for Multistory Applications.

1.5 – Current Use and Construction of Panels

Currently, CSIPs are limited to wall panel use in residential construction (governed by the IRC). Some companies detail roof panels, but comprehensive testing data on this use and use as a diaphragm is lacking. Because fiber-cement facing panels are limited to relatively small dimensions (e.g., 4’x8’, 4’x10’, and 4’x12’), all joints, connections, and penetrations must be properly managed, detailed, and constructed to provide adequate connection strength, proper moisture and water management, and reduced thermal shorts and bridges.

Figure 8 - CSIP Wall Construction

The following is a detailed guide that is typical in the industry. These details have been tested to all the relevant standards and have passed the weather barrier and thermal barrier tests. These details make some basic assumptions:

- Monolithic panels make up roughly 75% of typical residential envelopes with 90% of the panel being undisturbed (i.e., unbroken area);
- The splines and connection locations (horizontal or vertical) to other substructures make up the remaining 10% (nailed connection area) with localized drainage planes; and,
- Penetrations make up roughly 25% of all envelopes and should be limited to full panels (i.e., penetrations do not span multiple panels) with localized drainage planes and redundant layers of flashing.

For manufacturers, this means the panel shop drawings are based on window and door openings. These assumptions allow designers to assume the splines, connections, and penetrations can be made with localized drainage planes—multiple layers of water management and pressure equalization to allow moisture to move freely outside of the panel core—and additional layers to prevent water infiltration. Additionally, these detailing standards will encourage drying to the exterior and proper moisture management in any potential cavity. Basic standards include connections to substructures, splines, and all blocking in penetrations by the following standards. However, always consult your manufacturer for particular product specifications.

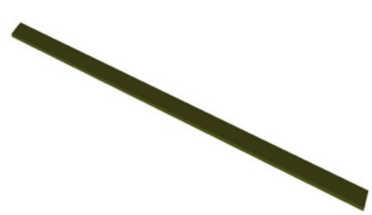
- Edge: 8d common nails, 6” o.c., ¼” from edges, 2” from corners
- Splines: 5.5” 19/32 OSB, 8d common nails, 6” o.c. ¼” from edges, 2” from corners
- Finishing: Prime entire envelope and openings with concrete masonry unit (CMU) block filler or equivalent to repair and patch any disturbed areas. Proceed with localized drainage planes and spaces around all penetrations.

Section 1.5.1 uses these standards unless otherwise noted.

1.5.1 – Installation of Typical Wall Panels

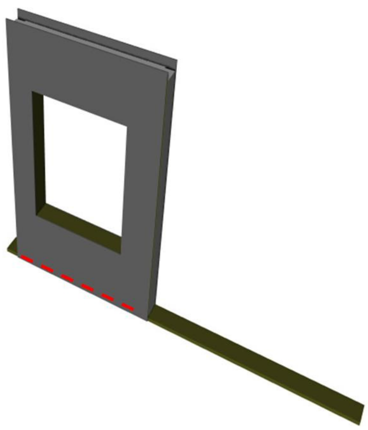
1. Installation of bottom plate—connection to foundation system or horizontal plate: Bottom plate is installed with a capillary break between plate and foundation. The bottom plate must be fastened and properly sealed to prevent air infiltration. Where required by code, metal Z-flashing can be installed on the outer face of the top plate-SIP for proper water management.

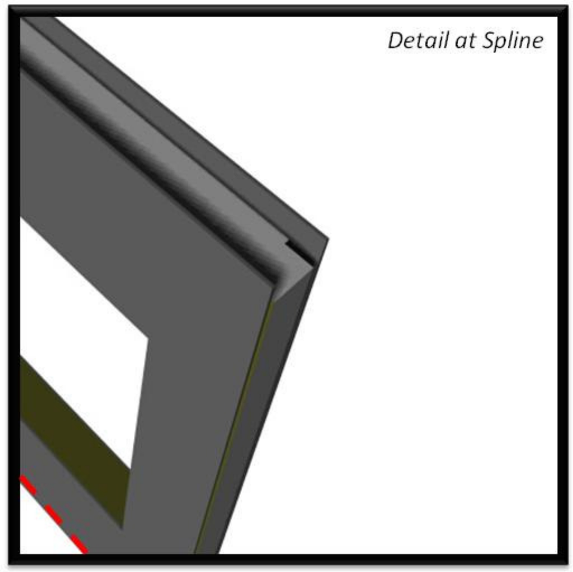
1. Installation to bottom plate



2. Installation of panel one: CSIP slips over bottom plate. Blocking installed in window penetrations at window opening. Note: window blocking installed at factory.

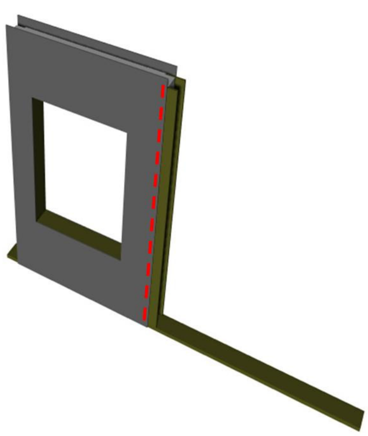
2. Installation of panel one

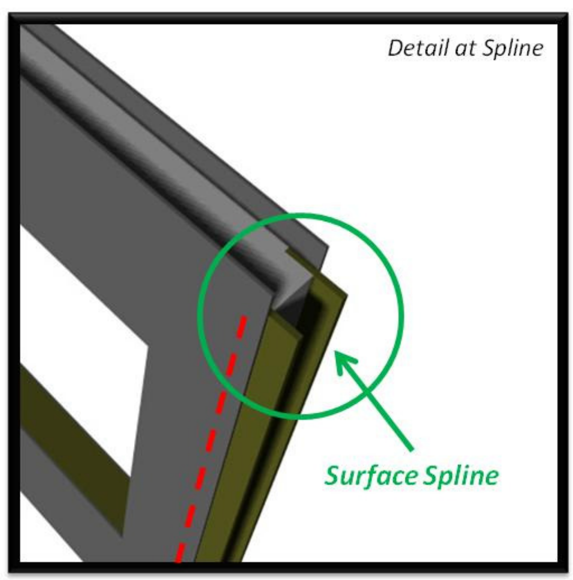




3. Installation of spline: Splines are comprised of 19/32 OSB or better splines, cut 5.5” wide to prevent telegraphing or “saw toothing” of panels. This detail recognizes the industry need to give generous spline widths and meet code minimums for fastening depth through the spline. More spline types are detailed later in this report.

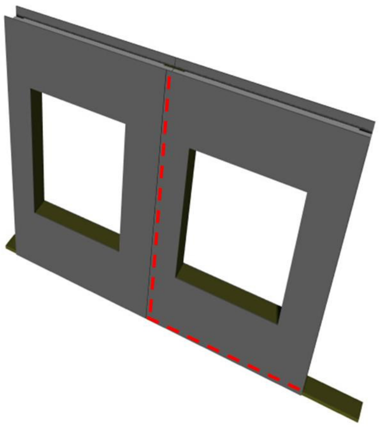
3. Installation of splines

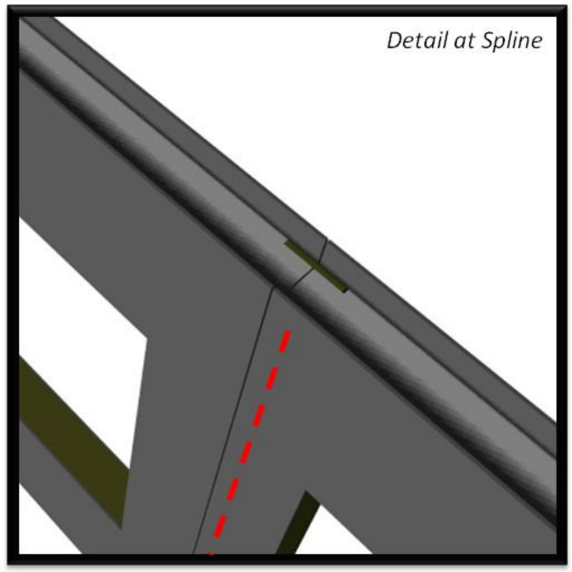




4. Installation of panel two: Refer to step 2.

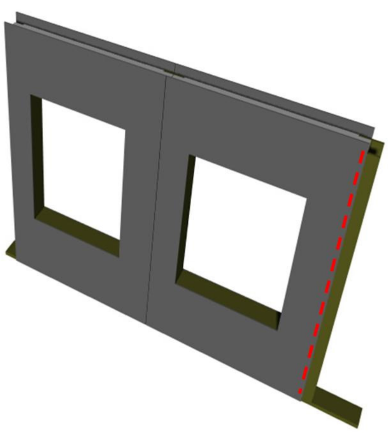
4. Installation of panel two

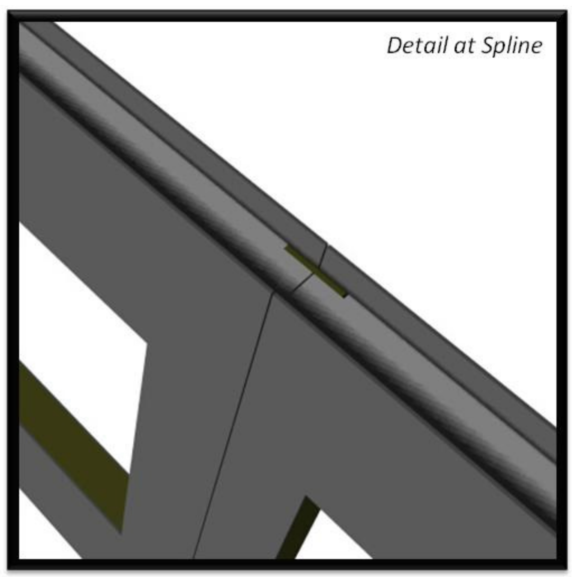




5. Installation of panel splines: Refer to step 3.

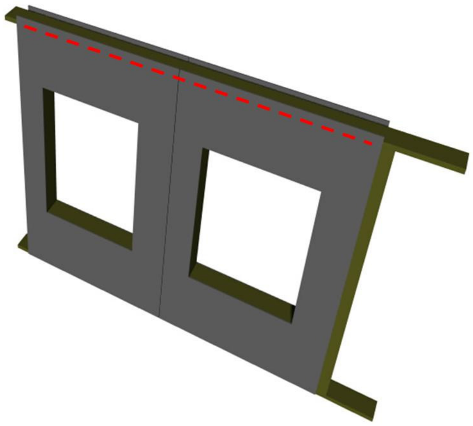
5. Installation of splines

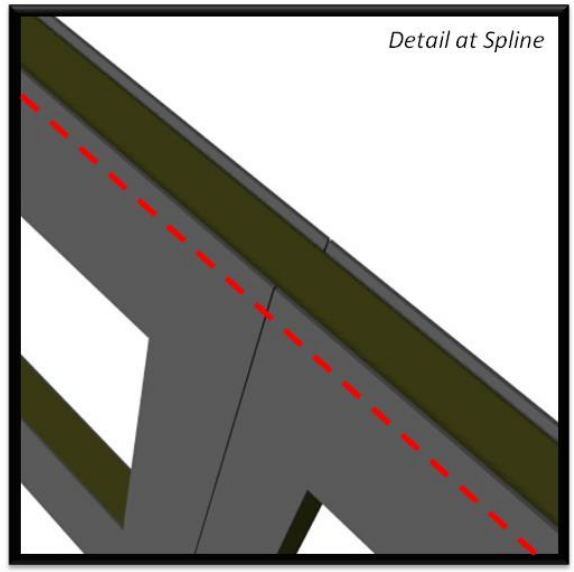




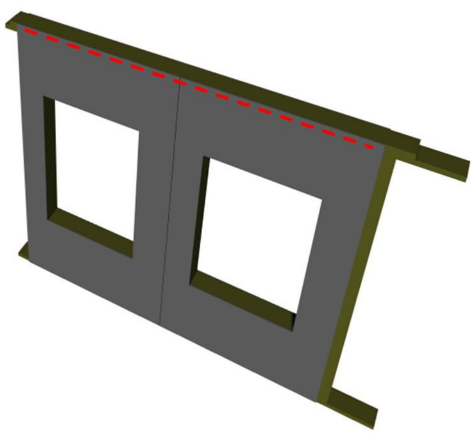
6 & 7. Installation of band plate and top plate: installed with 2x6 #3 or better. Plates must be tied together horizontally with and to the panel and must be tied together vertically.

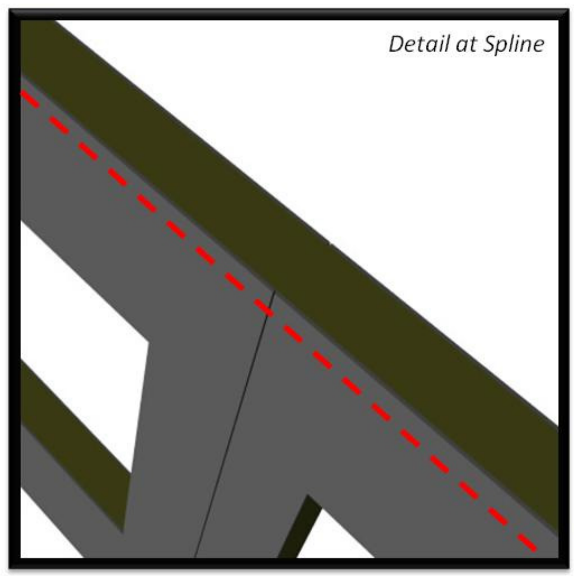
6. Install band plate





7. Install top plate





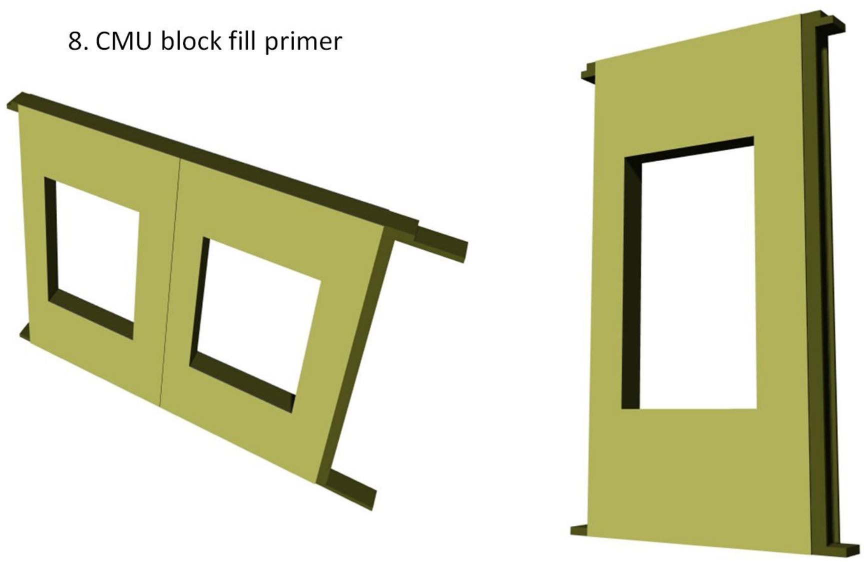
This concludes installing a basic panel. Subsequent panels tie directly into the installed panel to continue the wall plane.

1.5.2 – Construction of Weather Barrier and Window/Other Penetrations

The construction of the weather barrier follows. These details are shown both as an individual panel and as two combined panels.

8. CMU block fill primer: After all panels are set, the panels are primed to provide a continuous unbroken base finish using CMU block filler in all exposed surfaces and joints and potential surface defects and irregularities. The simple goal in this step is to specify a paint to fill imperfections, reduce water infiltration in pores, and seal all cracks and constructability issues. These paints should be specified with some latex qualities—such as elasticity to stretch and give.

8. CMU block fill primer

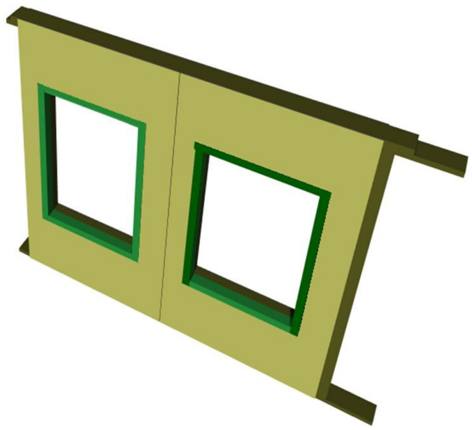


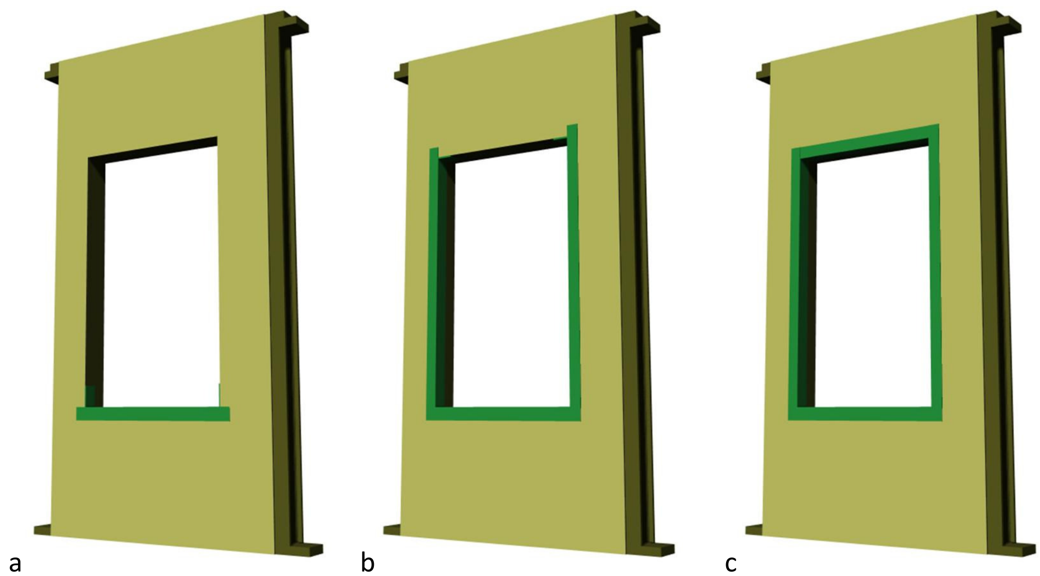
9a. Installation of pan flashing: Use self-adhering flexible flashing for pan flashing such as Dupont FlexWrap or StraightFlash to protect horizontal penetrations. This flashing must be cut so the ends extend past window openings. Fasten inner legs into jamb (minimum 1”) by slitting the flashing so one leg turns up the jamb and the other leg continues straight on the wall. Pan flashing must fit tightly into the opening. When using multiple pieces, pan flashing must overlap 3” at minimum. Note: if mechanical fastening is required, fasten only at the exterior face.

9b. Installation of jamb flashing: Use self-adhering flexible flashing protect vertical penetrations by cutting the flashing ends to extend past window openings. Fasten inner legs into jamb/head (minimum 1”) by slitting the flashing so one leg turns up the jamb and the other leg continues straight on the wall. The flashing must fit tightly into the opening; therefore, when using multiple pieces, pan flashing must overlap 3” minimum. Note: if mechanical fastening is required, fasten only at the exterior face.

9c. Installation of head flashing: Use self-adhering flexible flashing protect horizontal penetrations by cutting flashing only to fit into window to cover unprotected areas (i.e., use piece to overlap only in section unprotected by head). The flashing must fit tightly into the opening. When using multiple pieces, pan flashing must overlap 3” minimum. Note: if mechanical fastening is required, fasten only at the exterior face.

9. Installation of flashing





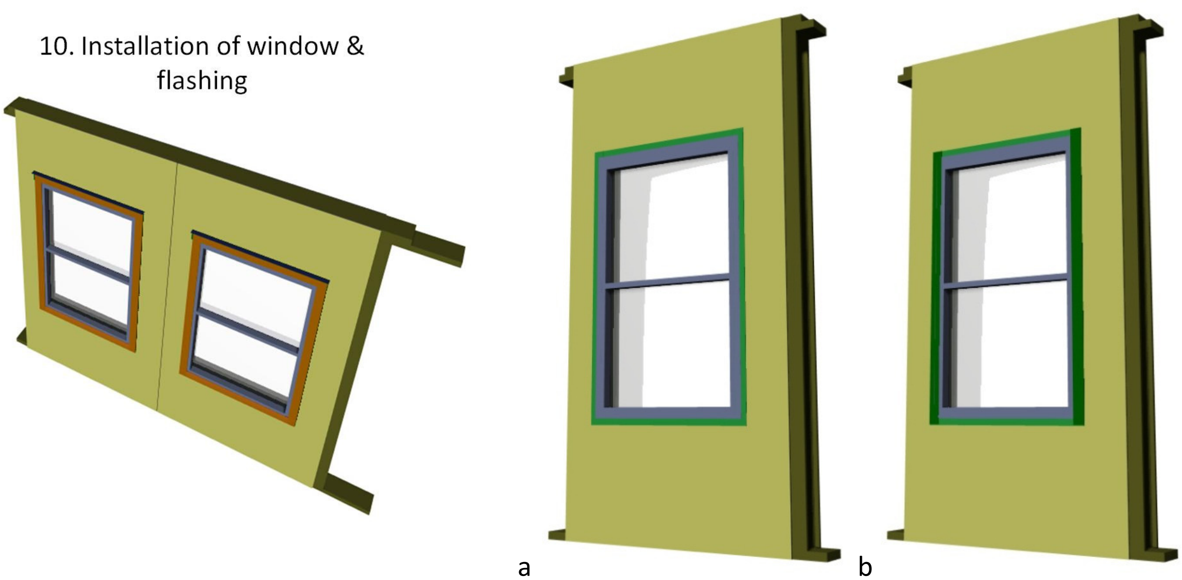
10a. Installation of window set: Only use windows with outer flange (i.e., nailing flange). Be sure to back caulk the window by applying sealant at window jambs and head. Use sealant at sill where required. Then set the window by installing the window level and plumb per the manufacturer's specifications.

10b. Installation of jamb flashing: Use self-adhering flexible flashing to protect vertical penetrations. Use continuous, unbroken piece (no mechanical fastening) and extend flashing above the window a minimum of 1" and below the window a minimum of 3".

10c. Installation of head flashing: Protect horizontal penetrations using self-adhering flexible flashing. Use continuous, unbroken piece (no mechanical fastening) and extend flashing 2" past jamb flashing.

10d. Installation of localized drainage space: Using polypropylene mesh deflection and ventilation system (or equivalent product to capture a void), provide a space for drainage to occur between the flashing and the trim pieces. An ideal product would be an equivalent tape, which could be stapled over the drainage planes to promote positive drain action within this space. This creates a cavity space to help manage water flow and drying to the outer wall.

10e. Installation of metal flashing: Install metal cap flashing above topmost trim by caulking joint between the metal flashing and the fiber-cement SIP. This is an important step because the drainage spaces and planes will allow any trapped water to move out of the assembly. However, the caulk will reduce the amount of water entering the space. This step should be considered a best practice.



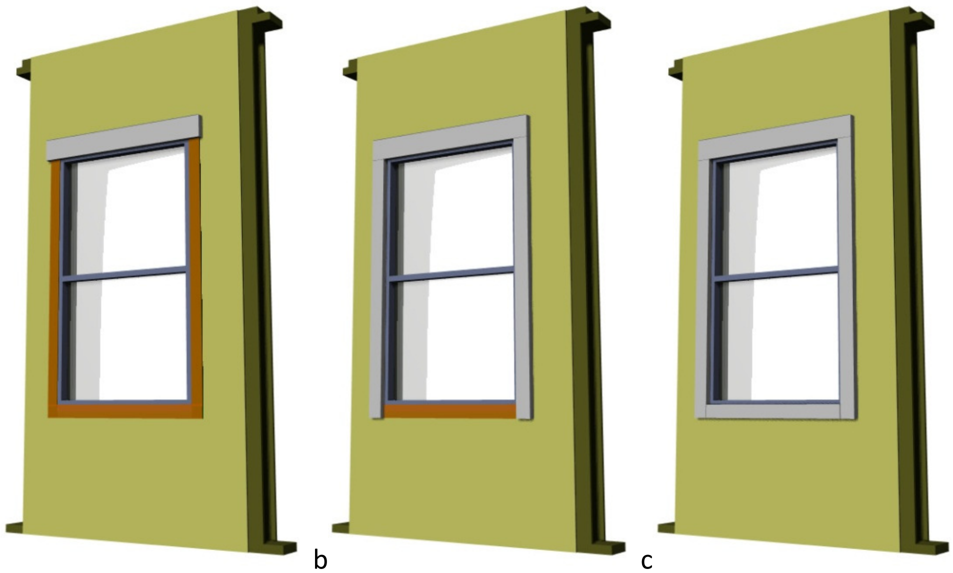
c

d

e

11. Installation of trim (a, b, c): Allow for positive drainage at all abutments and surface caulk all joints and other exposed areas. Follow the manufacturer's specifications.

11. Installation of trim



a b c

1.6 – The Current SIP Market

SIP usage has only been comprehensively tracked since 2003 through the industry trade association SIPA (Structural Insulated Panel Association). Currently there are roughly two dozen manufacturers and members in the association. This association represents some of the largest manufacturers in the industry but only a third to a half of the sandwich panel manufacturers in the United States. Domestic SIP production has remained near 50-60MN sq. ft. of panels annually which can easily be converted, to roughly a $250-450Mn market cap at market rates of $5-7.50 per sq. ft. SIP's annual growth has ranged from 2-12% annually until 2007 when the national new housing starts cooled and the industry shrunk, a projected, 11%.The reliability of these SIP numbers is questionable due to the small sample size and lack of standard reporting techniques.

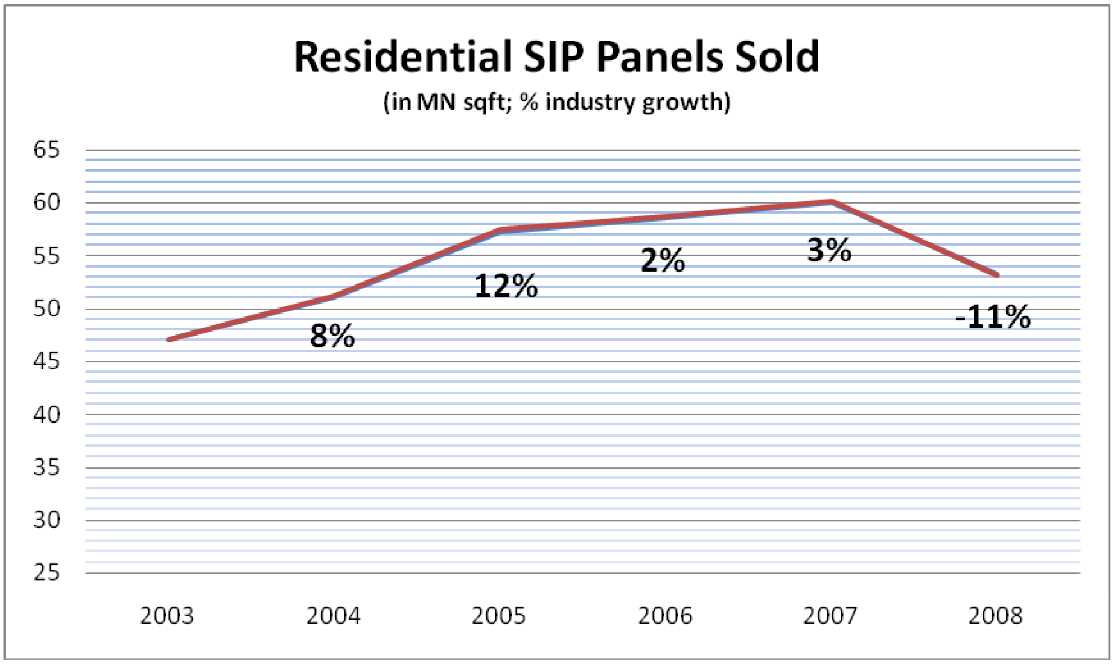


Figure 9 – Residential SIP Panels Sold, 2003-2008

Note: 2008 data is published in 2Q 2009 and not yet available at the time of publishing this report; 2008 projections (represented above) are based on conversations with Bill Wachtler of SIPA.

In 2007, the SIP market continued to be split evenly between residential and non-residential use. More importantly, SIPs can be broken down into panel types based on facings. Metal facings make up 50% of the market, followed by OSB on both sides (42%) and OSB on one side (6%). Plywood, fiber cement, and gypsum make up the remaining 2% of the market totaling 1.2M sq. ft. panels. Residential panel use is typically limited to OSB where non-residential use is typically comprised of metal. Metal SIPs are also used extensively in the refrigeration industry and for patio enclosures. Due to the current limitations of the Prescriptive acceptance of SIPs in the 2007 International Residential Code supplement, virtually all SIP buildings currently built are three stories or less.

Bill Wachtler, president of the Structural Insulated Panel Association, provided an update for this document prior to the official industry report to be published in second quarter 2009:

> "Although production of structural insulated panels (SIPs) has decreased slightly in 2007 and 2008, it has largely avoided the plight of the U.S. housing market, according to an annual survey conducted by the Structural Insulated Panel Association (SIPA). In 2008, a year when single family housing starts dropped by 40 percent, SIP production experienced only a [10-]13 percent decrease. Similarly, total SIP production grew nearly 5 percent in 2007 despite a 29 percent decline in single family starts. Survey results showed that although the industry's growth can be partially attributed to increased participation in the nonresidential market, it also indicates a

> sizable gain in residential market share [projected to have increased from 0.75% of all new housing starts to 1.0% of all new housing starts]."[11]

1.6.1 – Market Growth Potential

The CSIP (and larger SIP) industry currently faces many obstacles to growth, but it carries significant potential for expansion within current and new markets.

The major current problem is a significant lack of awareness and technical knowledge from owners, builders, architects, engineers, and the general public. If these key members in the construction process aren't aware of CSIPs, they will not specify their use. This problem is compounded by a shortage of case histories and case studies, a lack of standardization and specifications within the industry, and a lack of knowledgeable installers, as well as the diverse base of small manufacturers. In addition, fire resistance performance and building codes limit large-scale growth. These issues are addressed in Sections 1.7, 2.2.8, 3.5, and 4.2.

Like any new building system, a builder's first SIP construction project is likely to have problems. However, SIP construction has a fast learning curve, and we must avoid the perception that SIPs are difficult to install.

In addition, CSIPs face the need for industry development. Since the industry is small, production capacity is limited and slow to respond to market opportunities. Also, the CSIP supply chain is in its infancy and has only limited distribution channels and lacks a strong, national brand name. Growth depends on finding more CSIP manufacturer start-ups to generate demand for the product, rather than waiting for the OSB-faced SIP industry to recognize the new market value of CSIPs and expand to include the new material in production lines. The potential for product failure due to a lack of technical background, a lack of continued service after sale, and a concern that a poor quality product could ruin the SIP industry's reputation are other potential problems for such a young industry.

Finally, testing, national standards, and inconsistencies in manufacturing facilities slow the industry's growth. CSIP needs industry partnerships to leverage applications testing, including producing more data on the panels' seismic, moisture, durability, and weatherization. This testing must also work toward informing a standardized process for manufacturing and acceptance. CSIP manufacturers must develop and conform to consensus-based reference standards (ANSI). This formal development of processes and standards is important for a certified CSIP to spread and pick up new manufacturing locations.

Despite these obstacles, SIPs are gaining market share within the construction industry, which is good and bad for CSIPs. Within the SIP industry, the overwhelming trend is to use OSB facings, so the technical approach is focused on one facing material. Even so, this use is also spreading an awareness of SIPs as a building technology independent of facing materials, making the recognition of and transition to cement-fiber facings easier.

[11] Email correspondence and conversations between Joe Hagerman and Bill Wachtler of SIPA.

For CSIPs to become a recognized substitute to SIPs, it requires code recognition and the removal of building size limitations. In addition, CSIPs must work for inclusion in the SIP Prescriptive Method for the IRC, and must work to extend a similar prescriptive method accepted into the International Building Code (IBC). Without being accepted directly into the code, every CSIP project will require engineering to show compliance. Overcoming this step will make it much easier for builders to choose CSIPs for their building projects.

Despite these obstacles, SIPs offer many qualities that are becoming increasingly desirable, and there is tremendous opportunity for CSIPs in current and new construction markets. This opportunity is largely driven by rapidly increasing energy and construction costs, and the ever-growing interest in "green" building. Due to their inherent energy-efficient performance and ease of construction, CSIPs are an attractive candidate for addressing these variables. When paired with other energy-efficient and green technologies, CSIPs favorably affect a building owner's return on investment, asset turnover, opportunity cost, and environmentalism.

SIPs' composite nature makes them versatile and desirable for both single- and multistory construction. For both building types, CSIPs are an enabling technology that reduce substructure demands. CSIPs also offer an easily constructed, thermally efficient, cost-effective alternative building envelope. The wealth of materials and design options available allows considerable flexibility for new designs and uses.

In sum, CSIPs require significant development to fully embrace their potential. This report systematically compiles data based on the current CSIP industry and includes a detailed description of its potential extensions and future development.

1.7 – Current Limitations for Multistory Application

Two major factors currently limit the application of CSIPs to multistory construction: building codes and CSIP performance. Building code limitations will be explained here, while the latter will be discussed in-depth in Section 2.

Currently, CSIPs are used in construction up to three stories. This report uses the term "multistory" to focus on buildings above this threshold. While the applicable building code for a project is determined by the municipality providing the building permit, the majority of municipalities have adopted the I-Codes, a set of codes created by the ICC. The ICC has created distinct codes for one- and two-story residential construction (IRC), larger commercial and industrial construction (IBC), energy conservation in buildings (IECC), and more. *For multistory construction, the IBC is the most widely adopted code and will govern the majority of the buildings within the scope of this report.*

Despite this baseline, local codes dictate the decisions and understanding of acceptable CSIP applications.

The basis for panels used in multistory construction is restricted by the following:

- <u>Combustibility</u> (discussed in Section 2.2.8.1) based on ASTM E136 - 04 Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C and ISO 1182 Non-Combustibility Test for Building Materials limit CSIPs to:

    - Type V construction (three story maximum per Table 503); limitations dictated by the building code in Chapter 6, Types of Construction, and Chapter 5, General Building Heights and Areas, and
    - Exterior wall coverings in Type I buildings per 603.1.10.
- Fire Rating (discussed in Section 2.2.8.2) based on ASTM E119 - 08a Standard Test Methods for Fire Tests of Building Construction require CSIPs to conform to IBC 2603.4 Thermal Barrier. Note: each vendor must show compliance as a thermal barrier.
- Weather Barrier based on ASTM E331-00 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference require CSIPs to:
    - Conform to IBC 1403.2 as a weather barrier resistant to water intrusion and vapor permeance to allow drying while reducing vapor intrusion.
    - Weather barriers are manufacturer/vendor specific. Typical details shown in Section 1.5.3 have been known to pass the weather barrier requirements, but each manufacturer/vendor must show compliance as a weather barrier.
- Fiber-Cement Siding under IBC 1405.15 Fiber-Cement Siding as a Metal Veneer assembly (requiring the same fasteners, finishes, and other performance requirements of Metal Veneer assemblies.

The ways panels can be used in multistory construction are further limited by the following code provisions:

- Required fire ratings, Table 601 (discussed in 2.2.8)
    - CSIPs must obtain a fire separation distance greater than or equally to 30' (per Table 602) for exterior walls.
    - Joints in exterior walls are not required to have a fire rating (per 704.13).

TABLE 601
FIRE-RESISTANCE RATING REQUIREMENTS FOR BUILDING ELEMENTS (hours)

BUILDING ELEMENT	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
	A	B	A[e]	B	A[e]	B	HT	A[e]	B
Structural frame[a]	3[b]	2[b]	1	0	1	0	HT	1	0
Bearing walls Exterior[g] Interior	 3 3[b]	 2 2[b]	 1 1	 0 0	 2 1	 2 0	 2 1/HT	 1 1	 0 0
Nonbearing walls and partitions Exterior	See Table 602								
Nonbearing walls and partitions Interior[f]	0	0	0	0	0	0	See Section 602.4.6	0	0
Floor construction Including supporting beams and joists	2	2	1	0	1	0	HT	1	0
Roof construction Including supporting beams and joists	$1^1/_2$[c]	1[c, d]	1[c, d]	0[d]	1[d]	0[d]	HT	1[c, d]	0

For SI: 1 foot = 304.8 mm.

a. The structural frame shall be considered to be the columns and the girders, beams, trusses and spandrels having direct connections to the columns and bracing members designed to carry gravity loads. The members of floor or roof panels which have no connection to the columns shall be considered secondary members and not a part of the structural frame.

b. Roof supports: Fire-resistance ratings of structural frame and bearing walls are permitted to be reduced by 1 hour where supporting a roof only.

c. Except in Group F-1, H, M and S-1 occupancies, fire protection of structural members shall not be required, including protection of roof framing and decking where every part of the roof construction is 20 feet or more above any floor immediately below. Fire-retardant-treated wood members shall be allowed to be used for such unprotected members.

d. In all occupancies, heavy timber shall be allowed where a 1-hour or less fire-resistance rating is required.

e. An approved automatic sprinkler system in accordance with Section 903.3.1.1 shall be allowed to be substituted for 1-hour fire-resistance-rated construction, provided such system is not otherwise required by other provisions of the code or used for an allowable area increase in accordance with Section 506.3 or an allowable height increase in accordance with Section 504.2. The 1-hour substitution for the fire resistance of exterior walls shall not be permitted.

f. Not less than the fire-resistance rating required by other sections of this code.

g. Not less than the fire-resistance rating based on fire separation distance (see Table 602).

Figure 10 - Fire Resistance Rating Requirements for Building Elements [12]

[12] Table 601, 2006 International Building Code.

In addition, building height is limited by use and type of construction, per Table 503 of the IBC:

TABLE 503
ALLOWABLE HEIGHT AND BUILDING AREAS[a]
Height limitations shown as stories and feet above grade plane.
Area limitations as determined by the definition of "Area, building," per story

		TYPE OF CONSTRUCTION								
		TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
		A	B	A	B	A	B	HT	A	B
	HGT(feet)									
GROUP	HGT(S)	UL	160	65	55	65	55	65	50	40
A-1	S	UL	5	3	2	3	2	3	2	1
	A	UL	UL	15,500	8,500	14,000	8,500	15,000	11,500	5,500
A-2	S	UL	11	3	2	3	2	3	2	1
	A	UL	UL	15,500	9,500	14,000	9,500	15,000	11,500	6,000
A-3	S	UL	11	3	2	3	2	3	2	1
	A	UL	UL	15,500	9,500	14,000	9,500	15,000	11,500	6,000
A-4	S	UL	11	3	2	3	2	3	2	1
	A	UL	UL	15,500	9,500	14,000	9,500	15,000	11,500	6,000
A-5	S	UL	UL	UL	UL	UL	UL	UL	UL	UL
	A	UL	UL	UL	UL	UL	UL	UL	UL	UL
B	S	UL	11	5	4	5	4	5	3	2
	A	UL	UL	37,500	23,000	28,500	19,000	36,000	18,000	9,000
E	S	UL	5	3	2	3	2	3	1	1
	A	UL	UL	26,500	14,500	23,500	14,500	25,500	18,500	9,500
F-1	S	UL	11	4	2	3	2	4	2	1
	A	UL	UL	25,000	15,500	19,000	12,000	33,500	14,000	8,500
F-2	S	UL	11	5	3	4	3	5	3	2
	A	UL	UL	37,500	23,000	28,500	18,000	50,500	21,000	13,000
H-1	S	1	1	1	1	1	1	1	1	NP
	A	21,000	16,500	11,000	7,000	9,500	7,000	10,500	7,500	NP
H-2[d]	S	UL	3	2	1	2	1	2	1	1
	A	21,000	16,500	11,000	7,000	9,500	7,000	10,500	7,500	3,000
H-3[d]	S	UL	6	4	2	4	2	4	2	1
	A	UL	60,000	26,500	14,000	17,500	13,000	25,500	10,000	5,000
H-4	S	UL	7	5	3	5	3	5	3	2
	A	UL	UL	37,500	17,500	28,500	17,500	36,000	18,000	6,500
H-5	S	4	4	3	3	3	3	3	3	2
	A	UL	UL	37,500	23,000	28,500	19,000	36,000	18,000	9,000
I-1	S	UL	9	4	3	4	3	4	3	2
	A	UL	55,000	19,000	10,000	16,500	10,000	18,000	10,500	4,500
I-2	S	UL	4	2	1	1	NP	1	1	NP
	A	UL	UL	15,000	11,000	12,000	NP	12,000	9,500	NP
I-3	S	UL	4	2	1	2	1	2	2	1
	A	UL	UL	15,000	10,000	10,500	7,500	12,000	7,500	5,000
I-4	S	UL	5	3	2	3	2	3	1	1
	A	UL	60,500	26,500	13,000	23,500	13,000	25,500	18,500	9,000
M	S	UL	11	4	4	4	4	4	3	1
	A	UL	UL	21,500	12,500	18,500	12,500	20,500	14,000	9,000
R-1	S	UL	11	4	4	4	4	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000
R-2	S	UL	11	4	4	4	4	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000
R-3	S	UL	11	4	4	4	4	4	3	3
	A	UL	UL	UL	UL	UL	UL	UL	UL	UL
R-4	S	UL	11	4	4	4	4	4	3	2
	A	UL	UL	24,000	16,000	24,000	16,000	20,500	12,000	7,000
S-1	S	UL	11	4	3	3	3	4	3	1
	A	UL	48,000	26,000	17,500	26,000	17,500	25,500	14,000	9,000
S-2[b, c]	S	UL	11	5	4	4	4	5	4	2
	A	UL	79,000	39,000	26,000	39,000	26,000	38,500	21,000	13,500
U[c]	S	UL	5	4	2	3	2	4	2	1
	A	UL	35,500	19,000	8,500	14,000	8,500	18,000	9,000	5,500

Figure 11 - Allowable Height and Building Areas [13]

Please note each manufacturer should supply data (through evaluation or certification reports) that it has completed and verified proper testing demonstrating its system complies with the respective ICC codes. More information on this concept can be found in Section 4.2.

[13] Table 503, 2006 International Building Code.

2 – CSIP Performance

Section One of this research explained the basics of SIPs and the current state of the industry—material properties, basic mechanics, and performance variables. This section expands upon those basic ideas, elaborating on the specific performance criteria of CSIPs and how to interpret this data.

FAS has characterized performance variables in two sections: life-safety performance (e.g., structural characteristics, wind loading, impact resistance, seismic performance, fire resistance), and sustainable performance (e.g., energy efficiency and thermal performance, efficient use of materials, and life cycle costs.) CSIPs will be evaluated for each of these performance characteristics as a building technology, as well as within the scope of multistory applications. Each performance criterion will be explained, the relevant code criteria will be listed to determine code applicability, and the relevant required testing will be explained.

While the theoretical calculations behind each performance topic will be discussed, building professionals should not rely upon them as the sole source of information. Rather, physical testing of sandwich panels should inform the building professional's understanding of, as well as the design values for, CSIP performance.

2. 1 – Life Safety Performance

The major forces SIPs have to resist in building design include shear, transverse, and axial loads. However, they must also resist point impact forces, wind loads, and seismic forces to avoid failure. The values determining how CSIPs perform under these forces will be determined either by the prescriptive code or by test results from defined testing identified in the applicable acceptance criteria. Under the auspices of ICC AC04, the ICC compiled acceptance criteria for SIPs to "provide a procedure for recognition of sandwich panels in ICC Evaluation Service."[14] In addition to the principal tests described below, the AC04 Standards also feature information on connections, openings, plumbing and electrical installation, and other common conditions.

2.1.1 – Safety Factors

In addition to governing performance values, codes also dictate safety factors, which are multipliers applied to the maximum expected load to which a component or assembly may be subjected. Factors of safety (F.S.) as calculated by ICC are:

- F.S. = 2.0, ultimate load determined by bending failure for allowable live loads up to 20 psf (958 Pa) and wind loads.
- F.S. = 2.5, ultimate load determined by bending failure for allowable snow loads.
- F.S. = 2.5, ultimate reaction at failure for all loading conditions.

[14] ICC Evaluation Service, Inc., "Acceptance Criteria for Sandwich Panels: AC04", February 2004

- F.S. = 3.0, ultimate load at shear failure for all loading conditions.

In examining values from test results, it is important to distinguish between the ultimate load handled by the panel in testing and the allowable load after accounting for safety factors.

2.2 – Mechanical Behavior of Panels

As shown by the variety of facing, core insulation, and adhesive materials available, the variety of performance variables present in the design of SIPs allows for panels to be optimized specifically for each project. To do this properly, the basic mechanics of sandwich panels must be understood. The property of each material selection works within this framework of mechanics, making it important to understand the effects of geometry, materials, and construction on the overall composite performance outcome. This section discusses the foundations of panel analysis, explains the basis of stiffness-to-weight optimization design, and then explains common modes of failure for consideration in the design of sandwich panels and panel assemblies.[15]

This discussion of mechanics considers individual loading and isolated failure and does not consider the effects of combined loadings. Extensive testing should examine the effects of combined loadings on sandwich panel design for particular materials.

2.2.1 – Basic Panel Analysis

The effects of bending moments, transverse loads, and axial loads are discussed in the following sections. The resulting stresses form the foundation of understanding the various deformations and modes of failure possible in sandwich construction.

The following variables will be used in the discussion of panel analysis. They are listed here in order of appearance in the text:

σ = *Normal Stress*
σ_f = *Normal Stress of the Face*
σ_c = *Normal Stress of the Core*
τ = *Shear Stress*
τ_c = *Shear Stress of the Core*
M = *Bending Moment*
I_A = *Moment of Inertia*
y = *Distance from Neutral Axis of Cross-Section*
V = *Transverse Load*
Q = *Area Moment of Inertia*
t = *Thickness of Cross-Section at Point of Consideration*
P = *Axial Load*

[15] The analysis in this section is based largely on The Handbook of Sandwich Construction, ed. D. Zenkert. Consult this text for more information on sandwich construction, panel mechanics, and panel analysis.

E_c = Elastic Modulus of Core
E_f = Elastic Modulus of Face
A_c = Cross-Sectional Area of Core
A_f = Cross-Sectional Area of Face
Δ = Total Deflection due to Transverse Load
Δ_b = Deflection due to Bending
Δ_s = Deflection due to Shear
w = Uniform Transverse Load
L = Span Length
E_b = SIP Modulus of Elasticity under Transverse Bending
I = SIP Moment of Inertia per length
h = Overall SIP Thickness
c = Core Thickness
G = SIP Shear Modulus
V = Applied Shear Force
F_y = Allowable Shear Stress
C_v = Shear Correction Factor
M = Applied Moment
F_c = Allowable Facing Compressive Stress
F_t = Allowable Facing Tensile Stress
S = SIP Section Modulus for Flexure under Transverse Loads

Bending Moments

One advantage of sandwich panels is they can be designed with favorable stiffness-to-weight ratios. The case of a simply supported beam subjected to a bending moment can explain this.

The normal stress (σ) in a beam subjected to a bending moment (*M*) is inversely related to its moment of inertia (*I*), as shown in this formula:

$$\sigma \equiv \frac{M \cdot y}{I_A}$$

In sandwich construction, the faces experience far greater normal stress than the core (Figure 12 – Stress Distribution in a Composite Panel). By distancing the faces from the panel's center, the moment of inertia is increased. This decreases the normal stress in each face, enabling the beam to carry a greater load before yielding or failing.

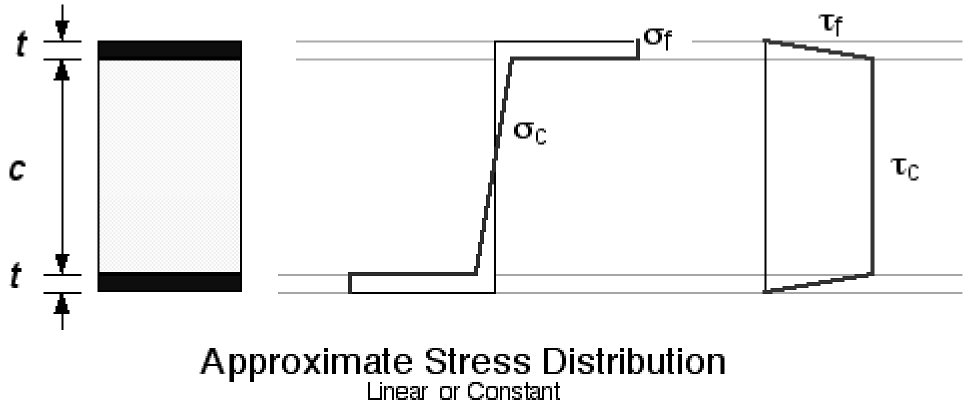


Figure 12 – Stress Distribution in a Composite Panel[16]

Modes of Failure of Sandwich Panels

Sandwich panels can fail in several ways (Figure 13 – Modes of Failure of Sandwich Panels). In addition to conventional modes of failure in beams or panels, their composite nature introduces additional design concerns such as bond strength. To understand the modes of failure possible in sandwich panels, it is imperative to understand the stress distributions across these panels. The following sections discuss the basic principles associated with each mode of failure. However, they do not discuss detailed equations for design because extensive testing for particular materials is preferable to traditional design calculations due to core, lamination, and facing variability.

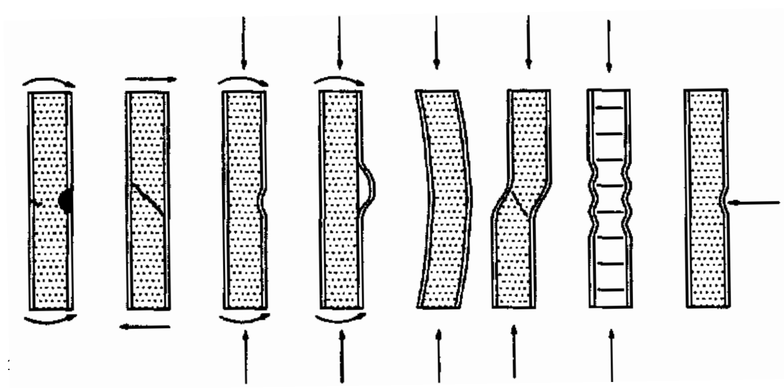


Figure 13 – Modes of Failure of Sandwich Panels

Yielding or Fracture Due to Tension or Compression:

Perhaps the most universal concern of beam and panel designs, normal stresses (tension or compression) due to bending or axial loads can cause catastrophic yielding or fracture (Figure 14 –

[16] Image adapted from http://www.mse.mtu.edu/~drjohn/my4150/sandwich/sp2.html
[17] Zenkert, D., 130.

Yielding of the Face (Tension)). In the case of sandwich panels, this type of failure often occurs in the face. This is primarily because the faces support greater normal stresses, as illustrated in Figure 13 – Modes of Failure of Sandwich Panels. Also, core materials are generally more ductile and have higher fracture strains. To design around this problem, Mohr's circle (or simple equations) can be used to calculate the maximum in-plane stress in the face.

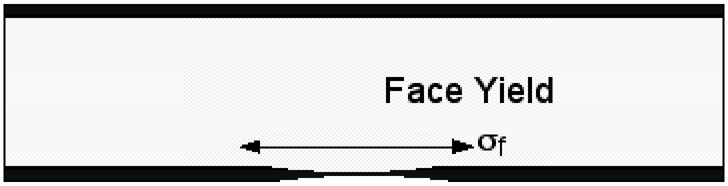


Figure 14 – Yielding of the Face (Tension) [18]

Shear Failure:

Just as normal failure is most commonly found in faces, shear failure generally occurs in the core of a sandwich panel. Earlier discussions of the resistance to transverse loads (Figure 12 – Stress Distribution in a Composite Panel) explain this: the higher resultant shear stress in the core may lead to failure. In addition, this failure occurs at 45 degrees (Figure 15 – Shear Failure of the Core).

Figure 15 – Shear Failure of the Core[19]

Wrinkling:

Wrinkling is the result of compressive forces in the face of a sandwich panel. The face either wrinkles inward or outward due to bending or buckling of the entire sandwich panel. If the compressive strength of the adhesive and core are low, the face will wrinkle inward, deforming the core. Conversely, if the tensile strength of the adhesive and core are low, the face will wrinkle outward. As Figure 16 – Wrinkling illustrates both inward and outward wrinkling can occur simultaneously. Face wrinkling can lead to further failure.

[18] Image adapted from http://www.mse.mtu.edu/~drjohn/my4150/sandwich/sp2.html
[19] Ibid.

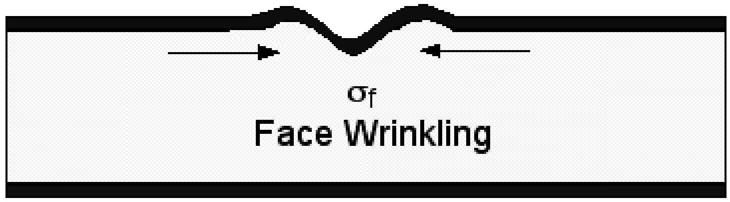


Figure 16 – Wrinkling [20]

Buckling:

In addition to causing normal failure, compressive forces can cause buckling in sandwich panels. While buckling itself does not necessarily constitute failure, it can cause catastrophic failure. As the shape and orientation of sandwich panels are altered by buckling, internal loads and stresses change. Ultimately, this deformation can result in compressive failure of the face, shear fracture of the core, or face wrinkling.

Bond Failure:

This type of failure is characteristic of composite materials such as sandwich panels. Joining different materials with adhesive introduces new points of failure into the design. Shear stress could cause the bond between face and core to fail. As shown in Figure 12 – Stress Distribution in a Composite Panel, the shear stress at the bond line is approximately as high as that of the entire core. If the panel is overloaded by a transverse load, the bond could fail. The design should take this into account. Fatigue, aging, and thermal stress can all cause bond failure. As insulators, the cores of the sandwich panels do not quickly absorb heat; however, metals and some other face materials do. This could cause an extreme temperature gradient at the interface, where the bond could break due to thermal stress. Using non-metal faces and working with small panels generally resolves design issues of thermal stress.

Fatigue:

Fatigue is an important concern in system design. While sandwich panels are generally found under either compressive or tensile loads, variation in these loads can shorten the lifetime of a panel system significantly. For this reason, both the face and core should be tested under applicable conditions, including load cycles due to wind, earthquakes, or human factors. If sufficient data on fatigue limits (for both the face and core) exists, it could be used in panel design. Each limit should be analyzed carefully, as normal stresses (σ_f) usually cause the faces to fail, while shear stress (τ_c) failure is common in cores. Different combinations of materials and adhesives should also be tested thoroughly to gain a deeper understanding of fatigue response.

[20] Ibid.

Modes of Failure of Fasteners

One of the most critical aspects of CSIP design is the performance of connections. Typical fasteners are provided by panel manufacturers and are suitable for most circumstances. However, in the case of specialized design or loading circumstances, panel connections may need to be designed.

Panel fasteners can fail in several ways. The following sections discuss the basic principles associated with each mode of failure. However, they do not discuss detailed equations for design because extensive testing for particular materials is preferable to traditional design calculations.

Concentrated Loads

Core indentation is one potential result of concentrated loads. While much of the analysis for sandwich panels can be simplified through assumptions such as Saint-Venant's Principle that ignore concentrated loads, the impacts of fasteners and other points of contact should be accounted for. In addition to considering the effects of fasteners on sandwich panels, the design of fasteners themselves must be completed carefully. They must stand up to the required loads without failing.

Vibration in Connections:

Vibration is one potential cause of fastener failure. Panel movement due to wind, human use, or ground conditions could result in fatigue failure. Extreme forces due to vibration or panel movement could even cause tensile or compressive failure of the fastener itself.

Thermal Stress in Connections:

Much like vibration, thermal stresses can cause fastener failure. Earlier, we discussed the effects of thermal stress at the face and core interface. Even if these thermal stresses do not result in bond failure, the effects could be translated to panel interfaces and fasteners. Fasteners should be designed to enable the expansion and contraction of face materials due to rapid temperature changes. If they constrain the panels, they could fail or deform the sandwich panels. Additionally, the effects of thermal stress on fasteners themselves should be considered in the design. However, these stresses rarely compare to the effects of panel movement and resulting stresses at the fastener-panel interface.

2.2.2 – Transverse Loads

A transverse load is a load applied perpendicularly to the plane of the longitudinal axis of a structure. How a panel deals with transverse loads is crucial for its performance in walls (dealing with wind loads), roofs (snow loads), or floors (the live and dead loads associated with occupancy).

Due to the relationship between transverse loads and shear stress, sandwich panels have advantageous characteristics for carrying these loads. In a similar fashion to the case of bending moments, the internal shear stress (τ) in a simply supported beam is inversely related to the moment of inertia:

$$\tau \equiv \frac{\mathrm{V} \cdot \mathrm{Q}}{I_A \cdot t}$$

In contrast to the case of normal stress due to bending moments (where faces experience the greatest stress), the core of the panel experiences the greatest shear stress due to transverse loads (Figure 12 – Stress Distribution in a Composite Panel).

TESTING:

To measure the performance of CSIPs in dealing with transverse loads, structural tests have been specified by ASTM International and the ICC in the standard building codes ratified by most municipalities.

The transverse load test measures deflection when a load is applied perpendicularly to the panel surface. For panels with brittle materials as facings, ICC requires “with a 5-pound-per-square-foot (239Pa) horizontal loading imposed, the interior wall panel deflections shall not exceed” L/240, where “L” is the length of the panel, for use under the following code standards: Boca National Building Code (BNBC), State Building Code (SBC), and the Uniform Building Code (UBC).

The ICC requires loads to be imposed in increments to failure, with deflections measured at each load. Deflection is monitored at “mid-span within 3 inches (76 mm) of each edge and at the center of the panel’s width.” ICC criteria for transverse load tests require “panels tested over a double span . . . to have the same three deflection readings taken at the expected maximum deflection point based on analysis.”

Transverse load testing is conducted in accordance with Sections 4.2 and 4.3 of ASTM E72 standards, where a panel is placed horizontally on two steel beams that function as framing members. Two equal loads are applied by two hydraulic cylinders, each placed at a distance of one quarter of the span from the supports, toward the middle of the span. ICC requires “a preload of approximately 10% of the anticipated ultimate load to be applied to ‘set’ the panel in the test apparatus” and the deflection to be recorded (see Figure 1 below). The panel is then loaded in increments to failure with deflection readings taken with each load at mid-span, within three inches of each edge, and at the center of the panel width. Deflection for the span is calculated by averaging the deflections obtained from each of the two micrometers.

RESULTS:

The following are sample test results from CSIP manufacturers demonstrating typical design test results and design values. Note that any values listed in this report should not be used in the engineering or design of a SIP building. Products differ with varied manufacturing techniques and quality control procedures, and only values from a certified report from a trusted third-party organization (the ICC-ES, IAS Guide 65 Product Certification Program, etc.) should be used in the engineering of a SIP construction project.

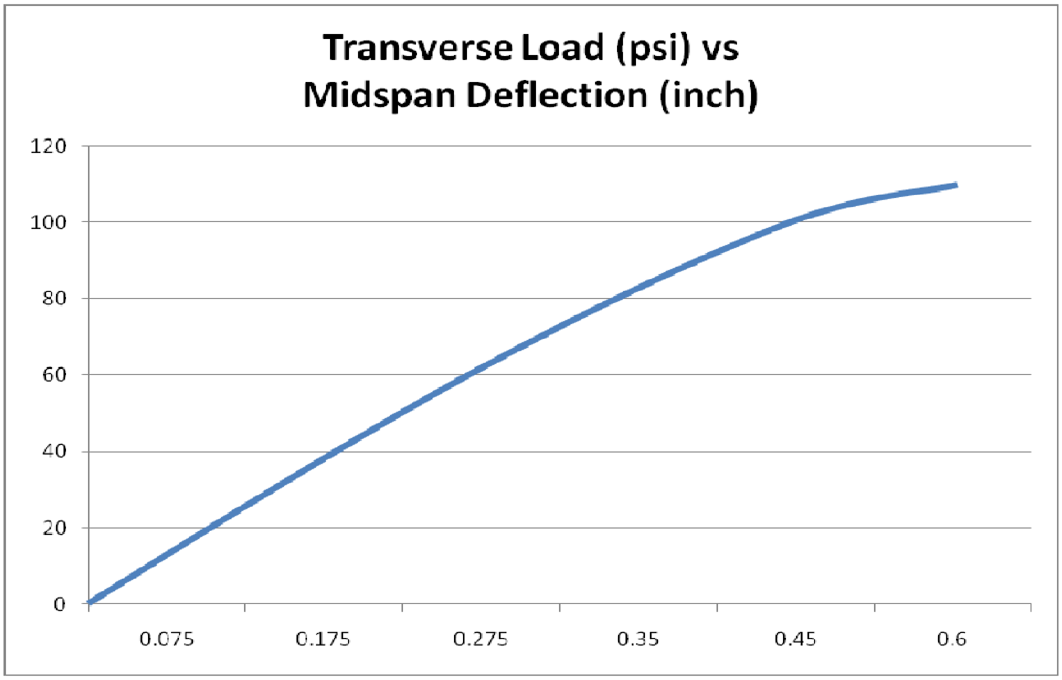


Figure 17 - Approximate Transverse Loading of CSIPs

The approximate design values for the transverse loading of CSIPs (with a safety factor of 3) is around 60 pounds per square foot (psf). However, actual design values should only be taken from manufacturer product evaluation or certification reports.

2.2.3 – Axial Loads

An axial load is a load applied along or parallel to and concentric with the primary axis of a structural member. The axis is typically in relation to a bearing wall or a column, and usually refers to vertical loads such as the weight of the building itself.

These loads result in normal stresses similar to those of bending moments. However, their distribution across the panel's cross-section does not have the same linear relationship. Using a combination of displacement and force equilibriums, the resultant normal stresses found in the face and core (constant throughout each) can be calculated as follows:

$$\sigma_c \equiv \frac{E_c \cdot P}{A_c \cdot E_c + A_f \cdot E_f}$$

$$\sigma_f \equiv \frac{E_f \cdot P}{A_f \cdot E_f + A_c \cdot E_c}$$

By calculating values using these formulae, the faces clearly experience higher levels of normal stress than the core. This stress level explains why the faces generally fail due to axial loads.

TESTING:

Per the IBC, axial loading must be accounted for if CSIPs will be used in any structural use, including concentrated loads, eccentric, and side loads. Test procedures developed by ASTM and specified in local codes must be followed. Axial load tests are designed to determine a panel's capacity to carry vertical loads from roofs, floors, and walls and to resist lateral loads from wind forces. The ICC Acceptance Criteria for Sandwich Panels requires that: "load-bearing wall panels shall support an axial loading applied with an eccentricity of 1/6 the panel thickness to the interior or towards the weaker facing material of an interior panel." ICC determines the allowable axial load by dividing the ultimate load by a factor of safety.

Allowed loads can also be established by finding the load at which the axial deformation is at or below 0.125 inches (if this load is lower than the load obtained by dividing the ultimate load by a factor of safety).

The test performed is a derivative of the test apparatus recommended by ASTM E72. A load is applied uniformly to the top of the panel, where two compressometers are placed two inches from each corner to read the axial compressive load. Deflectometers are positioned at mid-span to measure by how much the specimen deflects.

According to ICC, the allowable axial load is determined by dividing the ultimate load by a factor of safety. Factors of safety are explained above in Section 2.1.1 (usually a factor of 3.0 is used, since it incorporates all loading conditions).

RESULTS:

The following are test results from CSIP manufacturers demonstrating typical design test results and design values. Note that the values listed in this report should not be used in the engineering or design of a SIP building. Products differ with varied manufacturing techniques and quality control procedures, and only values from a certified report from a trusted third-party organization (the ICC-ES, IAS Guide 65 Product Certification Program, etc.) should be used in the engineering of a SIP construction project.

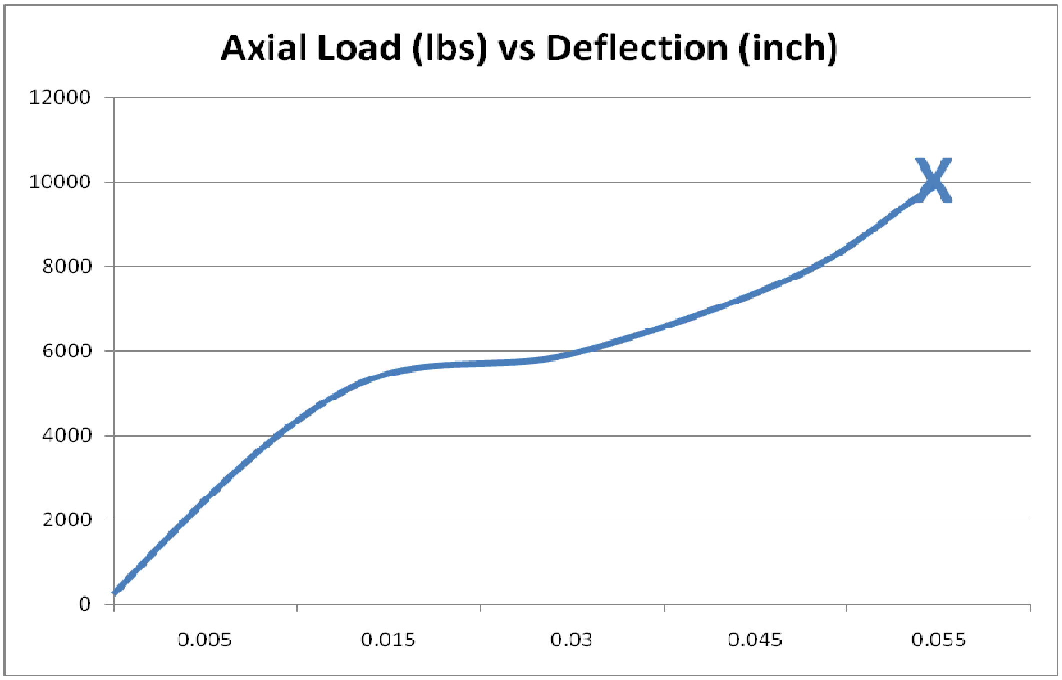


Figure 18 - Approximate Axial Loading of CSIPs

The approximate design value for the axial loading of CSIPs (with a safety factor of 3) is around 1400 pounds per linear foot (plf). However, actual design values should only be taken from manufacturer product evaluation or certification reports.

2.2.4 – Racking and Shear Loads

A racking load is a load applied in the plane of an assembly that lengthens one diagonal and shortens the other. A shear load is any applied external, translational load that creates shear stresses in a reacting structure. Per the IBC, if CSIPs will be used in any structural use, including shear walls, racking and shear loading must be accounted for. Racking and shear loads must also be accounted for in seismic zones. The requirements depend upon the local building code as well as any regional supplements.

TESTING:

Racking shear tests are required for shear walls that resist wind and seismic loads. According to the ICC Acceptance Criteria, the allowable shear load is determined from the racking load at which a net horizontal deflection of ½ inch (12.7 mm) occurs, or by dividing the ultimate load by a factor of safety as listed under the ICC Acceptance Criteria for Axial Wall Tests.

ASTM E 72 standards are designed to measure “the resistance of panels, having a standard wood frame, and sheathed with sheet materials such as structural insulating board, plywood, gypsum board, and so forth, to a racking load such as would be by winds.” Performance of the sheathing is, therefore, defined as the test objective. According to ASTM standards, the test set-up calls for the specimen to be attached to a timber or a steel plate. This plate is then attached firmly to the base of a loading frame in such a way that will not let racking bear on the loading frame. A hold-down is also required to prevent the panel to rise as racking load is applied, and since “the amount of tension in the rods of the hold-down may have an effect on the results of the test, nuts on the hold-down rods shall be tightened prior to load application so that the total force in each rod does not exceed 90 N at the beginning of the test as determined by previous calibration.”[21] Loading is then applied through the timber that is bolted to the upper plates of the specimen. Lateral guides and deflection measuring devices are required. Deflectometers should be located in the lower left (to measure any rotation of the panel), lower right (to measure any slippage), and upper right corners (the total of the two plus the deformation of the panel) of the assembly. Load is then applied continuously.

The panels were tested using a variant of the ASTM standard with some exceptions: the timber load distribution member recommended by ASTM was eliminated and was replaced with “a steel sleeve to fit over a short block glued to the top plate” and the apparatus for measuring deformation was simplified.[22] This method eliminated “the need for uplift, crushing and sliding gauges through the use of a light aluminum triangular frame resting on thin steel plates attached to the bottom plate.”[23]

RESULTS:

The following are test results from CSIP manufacturers demonstrating typical design test results and design values. Note that any values listed in this report should not be used in the engineering or design of a SIP building. Products differ with varied manufacturing techniques and quality control procedures, and only values from a certified report from a trusted third-party organization (the ICC-ES, IAS Guide 65 Product Certification Program, etc.) should be used in the engineering of a SIP construction project.

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[21] ASTM E72
[22] ASTM E72
[23] ASTM E72

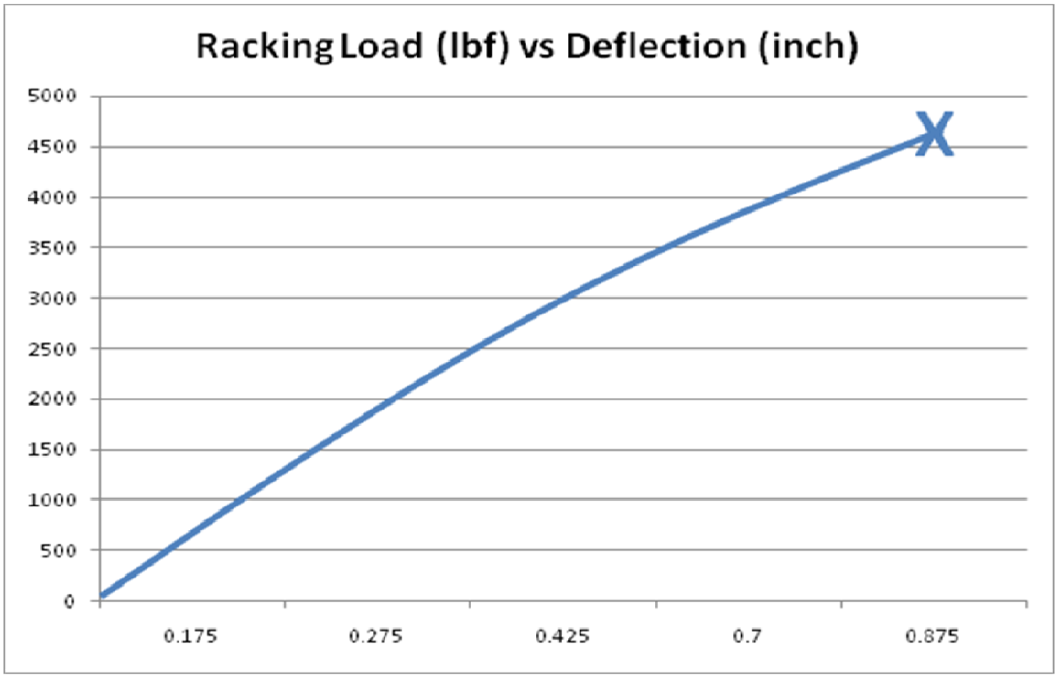

Figure 19 - Approximate Racking Loading of CSIPs

The approximate design values for the shear loading of CSIPs (with a safety factor of 3) are around 200 pounds per linear foot (plf). However, actual design values should only be taken from manufacturer product evaluation or certification reports.

2.2.5 – Wind Loading

With smaller buildings, a simple understanding of wind loading is acceptable: wind creates a uniform lateral pressure on the building's windward side and a suction force on its leeward side. However, as buildings rise higher, things become much more complicated. Wind is not constant either with height or with time, is not uniform over the building's side, and does not always cause positive pressure.

Although a general procedure follows, engineers should refer to the standard practice in their respected communities for wind design and evaluation. In general, following ASCE 7 or the local codes will determine the wind forces acting on the system. Using this information, professionals will generate the required cases to be tested concerning how the system is loaded given relevant conditions, safety factors, and design assumptions. The engineer must evaluate the system's basic loading, deflection, stresses, and the moments.

Code Requirements and Limitations

Buildings and their components must be designed to withstand the code-specified wind loads.[24] Per section 1609.1.1 of the IBC, wind loads shall be determined in accordance with Chapter 6 of ASCE 7. Wind pressures shall be assumed to be horizontal and normal to the surface considered.

Design loads for buildings governed by the IBC should be determined in one of three ways:[25]

a) a simplified procedure for low-rise, simple diaphragm buildings;
b) an analytical method for regular-shaped buildings; and
c) a wind tunnel approach for geometrically complex buildings.

Simplified Wind Load Calculation Procedure

The first approach is best used for determining and applying wind pressures in the design of simple diaphragm buildings with flat, gabled, and hipped roofs that have a mean roof height not exceeding the least horizontal dimension or 60 feet, whichever is less. This calculation requires determining the basic wind speed, the importance factor of the building, the exposure category, the height and exposure adjustment coefficient, and the simplified wind pressure. These values are combined to create the simplified design wind pressure for the main wind force resisting systems of low-rise simple diaphragm buildings. This design value represents the net pressure (sum of internal and external) to be applied to the horizontal and vertical projections of building surfaces. For the horizontal pressures, this is the combination of the windward and leeward net pressures.

More specific details for this calculation can be found in ASCE 7.

Analytical Procedure

Wind loads for buildings and structures that do not satisfy the conditions for using the simplified procedure can be calculated using the analytical procedure, provided that it is a regular-shaped building or structure and it does not have response characteristics making it subject to cross-wind loading, vortex shedding, or instability due to galloping or flutter, and it does not have a site location that requires special consideration.

The steps of analytical procedure are described in ASCE 7 Section 6.5.3. This procedure requires determining the basic wind speed, wind directionality factor, importance factor, exposure category or categories, velocity pressure exposure coefficient, the topographic factor, gust effect factor, enclosure classification, internal pressure coefficient, external pressure coefficients or force coefficients, and velocity pressure. How to determine each of these variables, as well as the design wind load, is determined through calculations and tables in ASCE 7. This design value differs for rigid buildings of all heights, flexible buildings, low-rise buildings, and open buildings and other structures.

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[24] Analysis adapted from http://ocw.mit.edu/NR/rdonlyres/Civil-and-Environmental-Engineering/1-051Fall2003/B56746CA-BF5C-4E25-AF42-418CF0C59202/0/rec1wind_eqloads.pdf
[25] Ibid.

Applying Calculated Design Loads to Panels

After calculating design loads upon a building design, the panel's performance should be verified. ASTM International has developed *ASTM E 330 Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference* for this evaluation. This test method describes the apparatus and the procedure to use for applying uniformly distributed test loads to a specimen.

FAS conducted computer-simulated and physical tests modeling the effect of heavy wind on the individual panels to demonstrate the panels' resistance deflection or collapse under extreme wind conditions.[26] The results were limited to showing performance of the panels under straight winds and do not give a clear idea of the performance under rotating winds, such as would occur in a tornado. Further testing on the joints attaching the wall panels and roof panel will give a better understanding of a panel building's potential resistance to the forces present in tornado conditions. Despite these shortcomings, however, this initial testing did demonstrate the panel's favorable performance in handling wind loads.

The computer-simulated panel homes exhibited excellent resistance to wind loads. The panel performance was measured in terms of the stresses exerted on each point of the walls and roof. The stress levels were mapped onto a model of the home and then evaluated to determine whether the maximum tension and compression exceeded the threshold at which the panel would be destroyed, defined as approximately 2000 kilopascals (290 pounds per square inch).[27] Stress levels were measured for each layer of the panel: however, the threshold stress level was determined assuming all elements of the panel would resist this level of tension or compression. Under each load combination, including wind, the stresses on the wall and roof panels remained below the destruction threshold.

Following the computational modeling, physical testing was performed. The 8'x8' test panels exhibited resistance to estimated loads of 15,000 to 18,000 lbs. An accurate determination of the failure load was not possible because the wooden planks serving as load distribution devices failed. The equivalent wind speed resistance, taking into account the safety factor of 3, is thus approximately 315 mph.

The physical and simulated tests for performance in high winds indicate the panels will resist high straight line wind, but further information on the performance of the joints in high wind or the entire structure in rotating winds would make the analysis more complete. Necessary tests include 1) an examination of the stresses on the adhesive connecting the cement board cladding to the EPS core of the panel under straight line and rotating wind loads, and 2) a test of the joints' resistance to tension and compression under straight line and rotating wind loads, with special attention to the horizontal diaphragm attachments.

Note: in designing with CSIPs, an individual panel manufacturer's testing data should be reviewed and used for these calculations.

[26] A full version of this report is included as Appendix D.
[27] Dr. Joseph Colaco, personal correspondence

Impact Performance

One of the performance variables related to wind loading is impact performance. Wind-borne debris in the event of high wind events such as hurricanes or tornados poses dangers for building envelopes. SIPs are not subjected to impact loads in regular use. However, impact damage can cause panel failure and should be understood when engineering.

Impact events on sandwich panels generally involve relatively high contact forces acting on a small area over a short period. Generally, when a sandwich structure is subjected to an impact, part of the energy associated with the impact is used for the elastic deformation of the material and returned back by the system. The energy in excess is dissipated through several mechanisms, such as fibers breaking, debonding, and delamination in the skins, while the core dissipates energy by crushing and shear deformation. The skin configuration and the core density control the impact behavior. In the case of an impact, the main performance of the foam core is limited to dumping the inertial loads.

Per the IBC, glazing in buildings shall be impact-resistant or protected with an impact-resistant covering meeting ASTM E 1996 and ASTM E 1886.

Computational analysis of SIPs is not enough to understand impact performance. A study conducted by the Materials Engineering Program at Auburn University focusing on impact testing of composite sandwich panels found the energy absorbed by a sandwich panel made of low-density foam core was about 15% to 100% greater than the sum of the energies its separate constituents absorbed. The impact resistance of composite sandwich panels was found to be mainly controlled by the facings if the facings were durable enough, yet controlled by the density of the foam core if not. This result indicates the impact energy of a composite sandwich panel cannot be predicted by the rule-of-mixtures law, and physical testing of panels is necessary to accurately predict performance.[28]

Engineers should refer to the standard practice in their respected communities for impact design and evaluation. In general, following ASCE 7 or their local codes will determine the impact load combinations acting on the system. Using this information about loading conditions, safety factors, and design assumptions, the professionals will generate the required load cases to be tested. In each of these load cases, the engineer must evaluate the system's basic loading, deflection, stresses, and moments. Different impact load combinations must be analyzed to determine the maximum deflection, shear stress, and moments resulting for the impact loads.

Unfortunately, impact performance of SIPs is not well established or researched within the industry. Because residential codes do not require impact testing of panels, existing panel manufacturers have not conducted testing. This is an area of necessary further research for the industry as CSIPs become more widely adopted.

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[28] Shih, W.K., and Jang, B.Z. "Instrumented Impact Testing of Composite Sandwich Panels", *Journal of Reinforced Plastics and Composites*, Vol. 8, No. 3, 270-298 (1989).

2.2.7 – Seismic

In addition to lateral wind loads, buildings must be designed to resist unpredictably dynamic seismic forces. While much of this resistance is the result of properly engineering a building to have a reliable load path, building materials and components play a critical role. For example, masonry buildings react significantly different than steel frame or stick built construction during seismic activity. Panelized construction provides a significant potential for dealing with seismic forces, as load paths can be easily anticipated and designed for (through panel connections), providing the proper ductility to absorb the energy of the seismic forces. This understanding of seismic performance requires an understanding of current code limitations for SIPs, as well as how to determine earthquake loads and how to evaluate panels in these regards.

Although a general procedure for analysis follows, the current building code (assumed to be 2006 International Building Code (IBC)) does not allow for the use of CSIPs and their added structural robustness solely due to the limitations dictated by the fire code—in particular the fact that all structural members must be noncombustible for multistory construction.

Code Limitations of Seismic Design In Multistory

Because the core of the CSIP is polymer based (including EPS, polyurethane, and XPS), its melting point will be significantly lower than traditional structural members, and therefore unsafe for consideration. Section 714 of the 2006 IBC clearly indicates the protection of "other structural members" should follow that of columns, girders, trusses, beams, etc. In particular, this section points out that seismic isolators, for example, must follow the fire rating of the columns as dictated in Table 601 and that the isolator must work the same after the fire as before the fire (i.e., after recovery). After CSIPs have been exposed to high heat—no fire required—most, if not all, of their ability to resist lateral loading will be severely diminished. Additionally, the connections between the building, substructure, and the CSIPs have not been optimized or thoroughly tested to resist and transfer lateral loads.

Per Section 1613 of the 2006 IBC, every structure shall be designed and constructed to resist the effects of earthquake motions in accordance with ASCE 7—Minimum Design Loads for Buildings and Other Structures, excluding Chapter 14 and Appendix 11A. This document, developed by the American Society of Civil Engineers, dictates the determination of earthquake loads for buildings within the scope of the IBC and is crucial to the scope of this research.

However, residential construction and Type V construction do not have this limitation, and the industry is currently evaluating SIPs and CSIPs for their seismic response factor, robustness, and connection optimization. Some of this research is funded by FAS and is recognized as critical to ensure long-term success as a product and to address code concerns.

FAS-sponsored research conducted by Professor Khalid Mosalem of the University of California–Berkeley could possibly overcome this roadblock. Mosalem employed the use of pseudo-dynamic testing to study the system performance of SIPs under seismic loading. While this research is still not widely known in the engineering community, a successful program could change the methodology adopted in AC130 for evaluating the SIPs for code compliance. This is especially important when the SIP industry reactivates the development of AC236 in the future. More information on this research will be included in as Appendix B.

Figure 20 – Small Scale Seismic Testing (OSB SIP Shown)

SIPs are not directly addressed in ASCE 7. This is a substantial issue for SIPs, as neither AC04 nor AC236 addresses the requirements for high seismic design categories (D and E) either. There is a new AC130, *Acceptance Criteria for Prefabricated Wood Shear Panels*, which can be used to develop design information for high seismic design categories. However, the International Code Council's Evaluation Service (ICC-ES) has been reluctant to adopt the AC130 methodology partly because of the pending AC236 development. T Therefore, up to this point in time, all ICC-ES evaluation reports on SIPs have not specifically recognized the use of SIPs in high seismic design categories. This restricts the market access of SIPs on the West Coast and in other seismic regions.

Determining Earthquake Loads

Understanding the seismic performance of CSIPs requires an understanding of determining the earthquake loads that must be designed for as well as an understanding of how those forces will act on (and be resisted by) the panel and panel configuration. The particle motion due to seismic forces is three dimensional, with x, y, and z components (x and y being considered horizontal, z being vertical). Building codes are mostly concerned with the horizontal components of ground motion and largely ignore the vertical component. Buildings are designed for vertical dead and live loads multiplied by a safety factor, and it is believed the safety factor will take care of any increase in stress caused by the vertical ground motion component.[29]

The process of determining earthquake loads can be broken down into the following basic steps, each of which is outlined in ASCE 7:

a) Determining the maximum considered earthquake and design spectral response accelerations
b) Determining the seismic base shear in conjunction with the structure's dynamic characteristics (e.g., fundamental period)
c) Distribution of the seismic base shear within the building or structure.

[29] Chelapati, C.V. (ed.). Seismic Design Review Manuel, 3rd Ed. Pg 2-74.

General Procedure for Determining Maximum Considered Earthquake and Design Spectral Response Accelerations

Ground motion accelerations, represented by response spectra and coefficients derived from these spectra, shall be determined in accordance with:

- the general procedure described in ASCE 7 Section 9.4.12 or IBC Section 1613.1, and
- the site-specific procedure described in ASCE 7 Section 9.4.1.3 or IBC Section 1613.5.3.

Conditions on using these methods depend on the seismic use group and site characteristics of the structure. The procedure for determining the design spectral response requires determining the mapped *maximum considered earthquake spectral response accelerations* at short periods and at a one-second period, determining the *site class,* the *maximum considered earthquake spectral response accelerations (adjusted for site class effects*), and the design spectral response accelerations at short periods and a one-second period. Using these parameters, the general response spectrum can be determined in accordance with ASCE 7.

Determining the Seismic Base Shear

Each structure shall be assigned a seismic use group (ASCE 7 Table 9.1.3), based on its corresponding occupancy category (determined from ASCE 7 Table 1-1) and a corresponding occupancy importance factor as indicated in ASCE 7 Table 9.1.4 and IBC Table 1604.5. All structures shall be assigned to a seismic design category based on their seismic use group and the design spectral response acceleration coefficients, S_{DS} and S_{D1}, in accordance with ASCE Table 9.4.2.1a or 9.4.2.1b, or IBC Table 1616.3(1) or 1616.3(2), whichever gives the most severe seismic design category.

The complex analysis procedures, which can be used within certain limitations, involve: index force analysis, simplified analysis, equivalent lateral force analysis, modal response spectrum analysis, linear response history analysis, and nonlinear response history analysis.

The seismic base shear in a given direction is determined from the seismic response coefficient, determined in accordance with ASCE Section 9.5.5.2.1 and the total dead load and applicable portions of other loads as indicated in Section 9.5.3.

Distribution of the Seismic Base Shear Within the Building or Structure

Once determined, the building design must be able to distribute these seismic forces within the building or the structure safely. How this is done is determined by the engineer and should be informed only by the design requirements and panels' design capacity values. This requires understanding how panels perform under seismic forces and how connections between panels are determined.

Evaluating Panels in Seismic Design

Per section 1708 of the IBC, the registered design professional is responsible for stating the applicable seismic qualification requirements for designated seismic systems. Each system component shall be tested by the manufacturer, with certification and results reviewed by the building official. This testing shall be by an actual test on a shake table, three-dimensional shock tests, an analytical method using dynamic characteristics and forces, the use of experience data, or a more rigorous analysis providing for equivalent safety.

Evaluating Panel Connections

The performance of a panel assembly under seismic forces is largely a function of its panel connections. However, the optimization of connections for seismic response is a significant unknown within the SIP industry, as no testing or testing protocol has been conducted. For the performance benefits of CSIPs to be recognized, this testing must be conducted and panel connections must be optimized for seismic performance.

2.2.8 – Fire Performance

A building's performance in the event of a fire is crucial to the life safety of its inhabitants. The spread of flames, the production of smoke and other noxious byproducts, and the structural failure of building components can harm building inhabitants. If building materials perform poorly in these situations, the risk of daily occupancy would be unacceptable. For this reason, extensive fire codes regulate materials and building design, and numerous tests have been standardized to evaluate a building's potential performance in a fire.

There are two distinct evaluations to be made regarding fire resistance for SIPs:

1) Combustibility and
2) Fire rating.

Combustibility

Combustibility refers to materials capable of burning, whereas a fire-resistance rating typically means the duration a system can withstand a standard fire resistance test. Both are regulated by code (in this situation, the 2006 IBC).

Classification on combustible and non-combustible construction is made based on the ASTM E136 - 04 Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C and ISO 1182 Non-Combustibility Test for Building Materials. In each of these tests, multiple specimens must survive without substantial mass loss for the specimen to be considered non-combustible. ASTM E136 and ISO 1182 are both severe tests.

EPS, the core of the majority of SIP products, is by itself combustible and has a relatively low melting point of 240°C. Polyurethane, another common core material for SIPs, has an even lower melting point of 150 to 175°C (depending on the formulation). No SIP material utilizing cores of polystyrene or polyurethane could survive 750°C and these severe tests. For that reason, SIPs are considered combustible construction and are limited for structural uses as Type V construction (three story maximum per Table 503) and have limitations stipulated by the building code in Chapter 6, Types of Construction, and Chapter 5, General Building Heights and Areas. If future core materials can be developed from noncombustible materials, SIPs' use and deployment may broaden in multistory construction; however, SIPs can be used as exterior wall coverings in Type I buildings per 603.1.10, "Combustible exterior wall coverings, balconies, and similar projections and bay or oriel windows in accordance to Chapter 14." As such, SIPs can be used as exterior wall envelopes, as defined in section 1402 of the IBC. Likewise, fiber cement can be used per 1402, 1405.15, and 1405.17. All exterior wall panels should demonstrate with testing they are weather barriers to protect and manage water infiltration.

Fire Rating

Because EPS is combustible, it cannot be exposed to flame or other ignition sources, and it must be protected by a thermal barrier equivalent to 15 min. exposures of gypsum (per 2603.4 Thermal Barrier). This determination relates to its fire rating, or its resistance to spread fire. Fiber-cement skinned SIPs have passed the ASTM E119 - 08a Standard Test Methods for Fire Tests of Building Construction and Materials to show conformance to 2603.4. Therefore, CSIPs do not need additional layers of protection to be used as fire-rated assemblies. However, they still have limitations as to their duration (fire rating), and each vendor must show compliance as a thermal barrier and weather barrier. Note: all fire rating values to be used in engineering equations should always come from a manufacturer's code report.

CSIPs have passed the E119 test to show applicability as a thermal barrier. However, the IBC further limits the fire separation distance (Table 602) of exterior walls. In particular, CSIPs must obtain a fire separation distance greater than or equal to 30'. Therefore, the density by which CSIP curtain walls can be to other buildings and structures is limited by their fire rating. Joints in exterior walls are not required to have a fire rating (per 704.13).

TABLE 601
FIRE-RESISTANCE RATING REQUIREMENTS FOR BUILDING ELEMENTS (hours)

BUILDING ELEMENT	TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
	A	B	A[e]	B	A[e]	B	HT	A[e]	B
Structural frame[a]	3[b]	2[b]	1	0	1	0	HT	1	0
Bearing walls Exterior[g] Interior	 3 3[b]	 2 2[b]	 1 1	 0 0	 2 1	 2 0	 2 1/HT	 1 1	 0 0
Nonbearing walls and partitions Exterior	See Table 602								
Nonbearing walls and partitions Interior[f]	0	0	0	0	0	0	See Section 602.4.6	0	0
Floor construction Including supporting beams and joists	2	2	1	0	1	0	HT	1	0
Roof construction Including supporting beams and joists	1 1/2[c]	1[c, d]	1[c, d]	0[d]	1[d]	0[d]	HT	1[c, d]	0

For SI: 1 foot = 304.8 mm.

a. The structural frame shall be considered to be the columns and the girders, beams, trusses and spandrels having direct connections to the columns and bracing members designed to carry gravity loads. The members of floor or roof panels which have no connection to the columns shall be considered secondary members and not a part of the structural frame.

b. Roof supports: Fire-resistance ratings of structural frame and bearing walls are permitted to be reduced by 1 hour where supporting a roof only.

c. Except in Group F-1, H, M and S-1 occupancies, fire protection of structural members shall not be required, including protection of roof framing and decking where every part of the roof construction is 20 feet or more above any floor immediately below. Fire-retardant-treated wood members shall be allowed to be used for such unprotected members.

d. In all occupancies, heavy timber shall be allowed where a 1-hour or less fire-resistance rating is required.

e. An approved automatic sprinkler system in accordance with Section 903.3.1.1 shall be allowed to be substituted for 1-hour fire-resistance-rated construction, provided such system is not otherwise required by other provisions of the code or used for an allowable area increase in accordance with Section 506.3 or an allowable height increase in accordance with Section 504.2. The 1-hour substitution for the fire resistance of exterior walls shall not be permitted.

f. Not less than the fire-resistance rating required by other sections of this code.

g. Not less than the fire-resistance rating based on fire separation distance (see Table 602).

2.2.9 – Mechanics Conclusions

Use of Panels: Sandwich panels are used to fulfill many different tasks in the same building. These panels must be able to support a variety of load conditions. Therefore, the intended use of each panel must be considered in the design phase. While floor panels can often be modeled as simply supported beams, this is not realistic for wall panels. In addition to obvious differences in load characteristics, the stresses in these different members due to human activities are pivotal to the successful design of such a structure. Finally, different fastener systems must be considered in conjunction with this panel design.

Need for Extensive, Case-by-Case Testing: Although the basis for design calculations was presented in this section, the complexity of such calculations prevents a full summary of panel engineering methodology. So many assumptions must be used to complete these analyses that the integrity of these calculations must be seriously evaluated. Several texts discuss the applicability of different methods of analysis, and these can be consulted for panel design.[30] However, extensive testing remains the best way to design sandwich panels. In sandwich panel construction, the results of theoretical calculations stray far enough from reality that they must be continuously tested and evaluated.

[30] For a thorough explanation of design calculations, see: H. G. Allen, *Analysis and Design of Structural Sandwich Panels*, Oxford: Pergamon Press, 1969, ch. 10 or D. Zenkert, *The Handbook of Sandwich Construction*, West Midlands, UK: EMAS, 1997, ch. 5.

Proprietary materials and adhesives also demand testing. The characteristics of each product will vary, and without extensive testing, it is difficult to establish material properties. This is true of most materials used in sandwich panel construction. Variation in proprietary products, unknown material properties, differences in fastening systems, complex assumptions in math-based design, and dynamic loadings all require extensive testing to determine the applicability and appropriateness of each panel system.

2.3 – Sustainable Performance Features

Sustainable building has become increasingly important to the building design community, with environmentally conscious design considerations rapidly gaining popularity. According to McGraw-Hill Construction Analysis, the value of green building construction exceeded $12 billion in 2008 and is projected to increase to $60 billion by 2010. With such momentum behind sustainability in the building industry, the green performance of CSIPs is an important consideration for designers and builders.

Unfortunately, determining definitions of "sustainability" or of "green" building and the related performance criteria are rather subjective, and there are no clear industry standards. FAS chose *ASTM E2432: Standard Guide for General Principles of Sustainability Relative to Buildings* and the *Whole Building Design Guide* as guidelines for determining the sustainability performance characteristics that relate to CSIPs. ASTM E2432 provides a good overview of the direct and indirect environmental, economic, and social impact of buildings, as well as the process of implementing these principles into real-world building applications. The Whole Building Design Guide approaches sustainability in the same way, looking at the composite performance of the building and identifying the important steps. While these resources focus on an entire building, some principles they identify pertain to CSIPs, including energy efficiency, the use of natural resources, the production of construction waste, and indoor environmental quality. In addition to these performance criteria, FAS has evaluated SIPs in relation to the U.S. Green Building Council (USGBC)'s Leadership in Energy and Environmental Design (LEED) rating system, the nation's leading green building certification system.

The sustainable performance criteria must simultaneously consider the functions of energy efficiency, thermal efficiency, and building tightness (through the thermal, weather, and air barriers). One of the principal reasons for selection of CSIPs is their insulation qualities. Additionally, the system supports lower glazing to wall area ratios, which dominated buildings before glass curtain wall construction was commercialized. In this regard, there is a greater unbroken area of traditional insulation than glazing. Also, because the glazing area is smaller, the glass and window unit can be of a higher quality and use low-e glass to minimize the penetration points for decreased air infiltration. However, as a design strategy, to fully leverage the sustainable performance of the assembly, all connections and details must be considered to reduce air infiltration, reduce thermal bridging, and optimize production and structural capacities. These issues will be further addressed in this report's design guide.

2.3.1 – Energy Efficiency

Buildings are one of the heaviest consumers of natural resources and account for a significant portion of the greenhouse gas emissions that affect climate change. In the United States, buildings account for 38% of all CO_2 emissions.[31] The majority of these emissions come from the massive amounts of energy buildings use. Buildings represent 39% of the United States' primary energy use and 70% of its electricity consumption.[32] In a 2007 report on climate change mitigation and greenhouse gas reduction, the McKinsey Quarterly determined improving energy efficiency in buildings through better insulation to be the highest-impact, most cost-effective abatement approach.[33]

With this in mind, the energy-saving potential of building with CSIPs is their most apparent sustainable advantage. A CSIP building envelope provides high levels of insulation and is extremely airtight. This means significantly lower operating costs for a homeowner, as well as a smaller contribution to the energy use and carbon emissions from your building.

Although the energy efficiency performance of a CSIP building is somewhat inherent to the system design, it is tied directly to the detailing and construction of panel connections. If these connections are not properly constructed, thermal bridging may be present, reducing the whole wall R-Values that make CSIPs beneficial. Also, improper construction can allow for increased air exchanges through wall cavities, reducing the efficiency of ventilation systems and energy efficiency.

Where applicable, typical panel connections are explained herein. However, a further discussion of these construction issues can be found in Section 3.2.

Thermal Performance

One of a building's most basic functions is to create a different, controlled thermal environment for its occupants. A building system's ability to do this effectively is crucial to its overall value and correlates directly to the amount of energy it uses.

Energy flow through building panels and wall assemblies are primarily driven through two mechanisms:

1) Temperature-driven heat transfer, and
2) Infiltration.

Temperature-driven heat transfer is the differential between the inside and outside temperature—heat is either lost or gained through the section, frame, and panels. This is indicated in terms of the U-factor or R-factor of the assembly ($U=1/R$). Infiltration is heat lost or gained through the air infiltration through cracks in the assembly. This negative effect is measured in terms of the amount of air that passes through a unit area of the panel under different pressure conditions. Infiltration is thus driven by wind-driven and temperature-driven pressure changes and fluctuations. Infiltration may also contribute to interior humidity.

[31] EIA Annual Energy Review 2005. U.S. Energy Information Administration, U.S. Department of Energy.
[32] 2003 U.S. DOE Buildings Energy Databook.
[33] McKinsey Report

Not all CSIPs have the same thermal performance because of the materials used and the construction standards. CSIPs can be made thicker with more insulation, having a higher insulating value (R-value) and transferring less heat dependent on the spline conditions. However, it is not enough to judge their effective thermal performance by simply noting this R-value. This assumes a wall is entirely filled with insulating material and makes for a poor and misleading comparison of building systems. This assumption is especially misleading because most building systems have small conductive elements that penetrate or go around the insulation to create thermal bridges—"thermal shorts"—through which heat can travel. Thermal bridges significantly lower the effective insulation value and create unanticipated temperature gradients that can lead to thermal stress, condensation, and other effects. For example, high-performance window systems often have a narrow aluminum spacer (roughly 13 mm) between glazing layers. This thermal bridge can increase the total heat transfer through the window by 50%.[34]

To avoid these simple misconceptions, FAS has based thermal performance calculations on the finite-element analysis of a steady-state, two-dimensional heat transfer software. The software, called THERM, was developed by Lawrence Berkeley National Laboratory (LBNL). Once a cross section's geometry, material properties, and boundary conditions are defined in the program (all known quantities in a wall assembly), THERM meshes the cross-section, performs the heat-transfer analysis, runs an error estimation, refines the mesh if necessary, and returns the converged solution.[35] These results show more than just the R-value of the insulating components. They allow the user to evaluate a building component's energy efficiency and local temperature patterns, demonstrating the effective thermal performance of the entire assembly. We recommend using THERM to evaluate any final design to ensure "thermal shorts" are kept at a minimum.

THERM examines temperature-driven heat transfer in a static two-dimensional state. Conduction, convection, and radiative heat transfer are considered. Conduction is the heat traveling through a solid material, convection is the transfer of heat by the movement of gases or liquids through a system, and radiative heat transfer is the movement of heat energy through space without relying on conduction through the air or by movement of air.

Because SIPs are a system assembly, almost a kit of parts, it is easy to evaluate temperature-driven heat transfer and infiltration simultaneously simply because all infiltration points are also points where direct temperature-driven heat transfer is applied. These locations are confined to the perimeter or boundary of the panels. Therefore, we must consider constructability, weatherization, and thermal barriers as well as spline condition, type, and so forth. To accomplish this, FAS modeled the different panel connection types to determine the preferred designs. A few conclusions must be discussed:

- Thermal bridging is the primary means for heat transfer between panels at all connections.
- Thermal performance of splines can be modeled, studied, and optimized using THERM.[36]

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[34] THERM 2.0: A BUILDING COMPONENT MODEL FOR STEADY-STATE TWO-DIMENSIONAL HEAT TRANSFER

[35] For more information on THERM see, www.lbl.gov

[36] "Therm 2.0: A Building Component Model For Steady-State Two-Dimensional Heat Transfer," Charlie Huizenga et al, May 1999; also "Rating And Labeling Of Energy Performance Of Windows As A Tool For Promoting Energy Efficiency Practices In Buildings," Bipin Shah et al (unknown date)

NOTE: Engineers should develop structural components, then model joints and connections for both structure and heat flow. Easy methods to optimize joints are shown herein.

The following spline conditions were modeled in THERM and modeled as a physical assembly (showing the fiber-cement siding (green), EPS (gray), and metal sections (purple)). Also, the infrared analysis showing heat transfer through the assembly and the gradations are illustrated. The infrared sections help illustrate areas where heat flow is greater than the baseline. Gradual, defined, and uniformed gradations are ideal. For all assemblies, the calculated R-value is given and the percent error in the solution. A 6.5" panel was assumed.

BASELINE: Blank panel is baseline, optimum case, results in connections inside or outside the envelope. The R-factor is 25 (0% error).

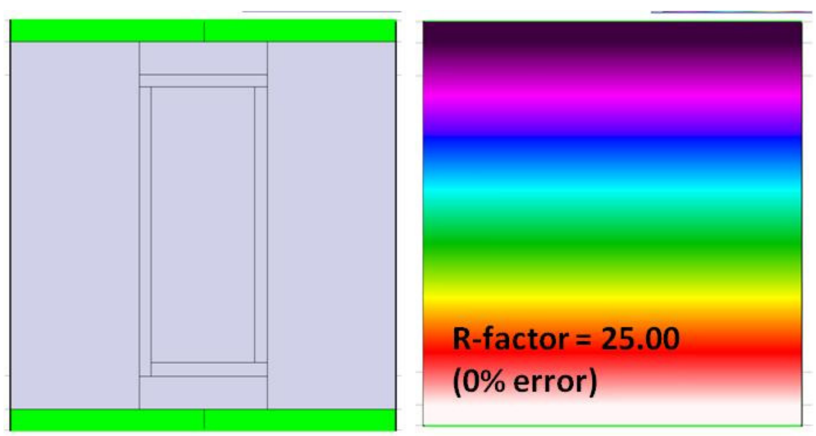

Figure 21 – Infrared Thermal Analysis Diagram of a Blank SIP (baseline)

SURFACE SPLINE: Surface splines are common in residential construction, and may have commercial applicability if metal is used. Factors to consider are connector to facing interface, strength, durability, and performance as a thermal/weather barrier. The R-factor is 23.26 (4.5% error).

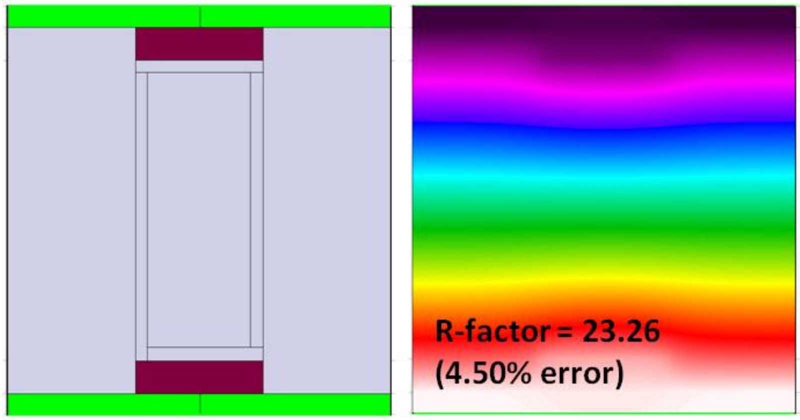

Figure 22 – Infrared Thermal Analysis Diagram of SIP with Surface Spline

FULL SPLINE: Full splines are the least thermally effective spline detail and provide a direct thermal short at all spline locations; however, it has the largest section area for additional support or point loads. The R-factor is 5.71 (7.95% error).

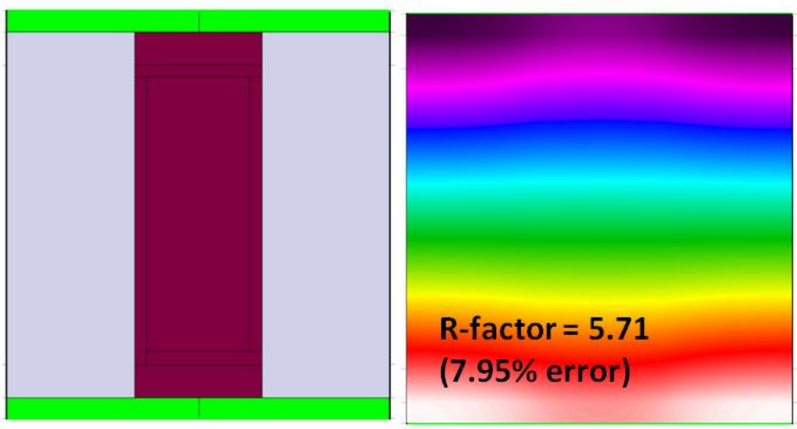

Figure 23 – Infrared Thermal Analysis Diagram of SIP with Full Spline

GUARDED SPLINE: Guarded splines are more efficient full splines separated from the facings with insulation; fasteners are tied into this member but allowed to rack. The R-factor is 11.49 (6.56% error).

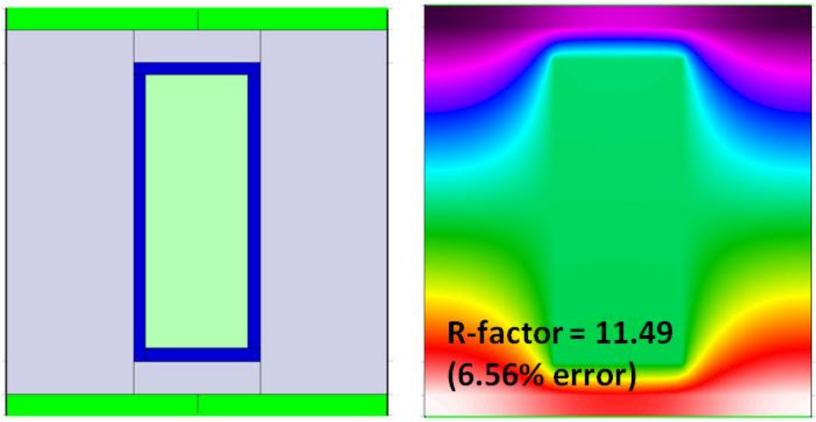

Figure 24 – Infrared Thermal Analysis Diagram of SIP with Guarded Spline

OFFSET SPLINE: Offset splines are hybrid splines allowing on-side direct fastening and the other side some racking in its fastening to the member. The R-factor is 8.67 (7.61% error). This spline type may cause eccentric or asymmetrical loads within the panel and needs further study.

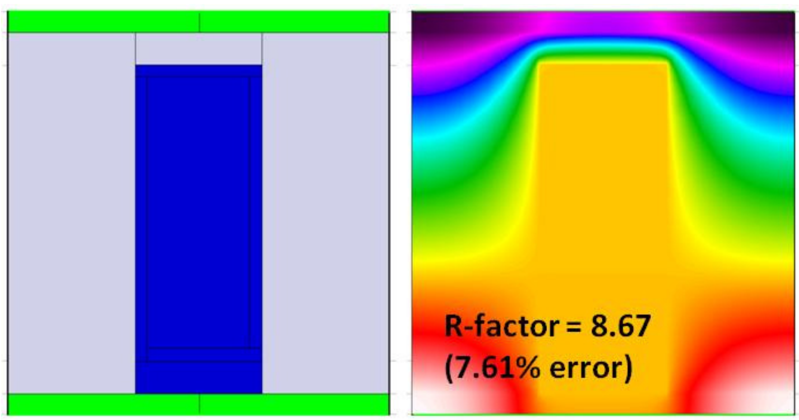

Figure 25 – Infrared Thermal Analysis of SIP with Offset Spline

GUARDED OFFSET SPLINE: Guarded offset splines may be the preferred design because they allow for a large sectional area to be directly fastened and surface splines to make up the other face. The R-factor is 14.10 (8.99% error). This spline type may cause eccentric or asymmetrical loads within the panel and needs further study.

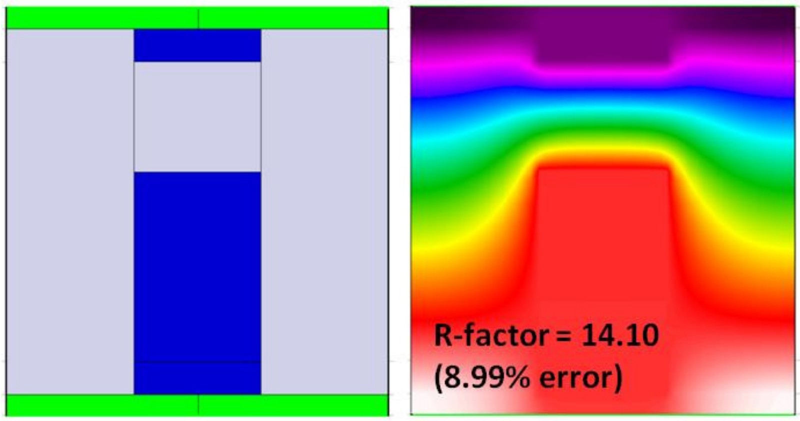

Figure 26 – Infrared Thermal Analysis of SIP with Guarded Offset Spline

Conclusions and limitations:

Wall details are primarily derived from residential construction and may need further modification for commercial use given construction/material handling. Wall details are adapted from standard practice and may not be optimum in terms of balancing the infiltration, heat transfer, and constructability. The performed thermal analyses are general in nature, and it is recommended that each project run specific evaluations, for the thermal analysis has varying section moduli and areas. Thermal analysis does not fully take into account the structural differences. Overall, more research is needed in splines and optimum splines/connectors.

Typological Connection Type & Relative Performance

	U-factor	R-factor	Error
Blank panel (baseline) *Assumed baseline panel*	0.0400	25.00	0.00%
Wood Surface Spline	0.0416	24.04	1.70%
Metal Surface Spline *Preferred panel to panel connection.*	0.0430	23.26	4.50%
Full Wood Spline	0.0580	17.24	1.20%
Full Metal Spline	0.1752	5.71	7.95%
Guarded Metal Tube	0.0862	11.60	6.53%
Guarded Metal Solid *Preferred substructure panel connection.*	0.0870	11.49	6.56%
Metal Offset Spline	0.1154	8.67	7.61%
Guarded Metal Offset Spline *Preferred substructure panel connection.*	0.0709	14.10	8.99%

Note: assume 5.5" insulation core throughout.

Figure 27 – Relative Thermal Performance of SIP Connection Types

This improved performance of SIPs is confirmed in a study of whole-wall R-values conducted by the Oak Ridge National Lab. The study accounts for heat loss through windows, doors, corners, and slab connections. The results demonstrate the benefits of SIPs—the lack of thermal shorts creates a whole-wall R-value higher than conventional wood-framing construction.

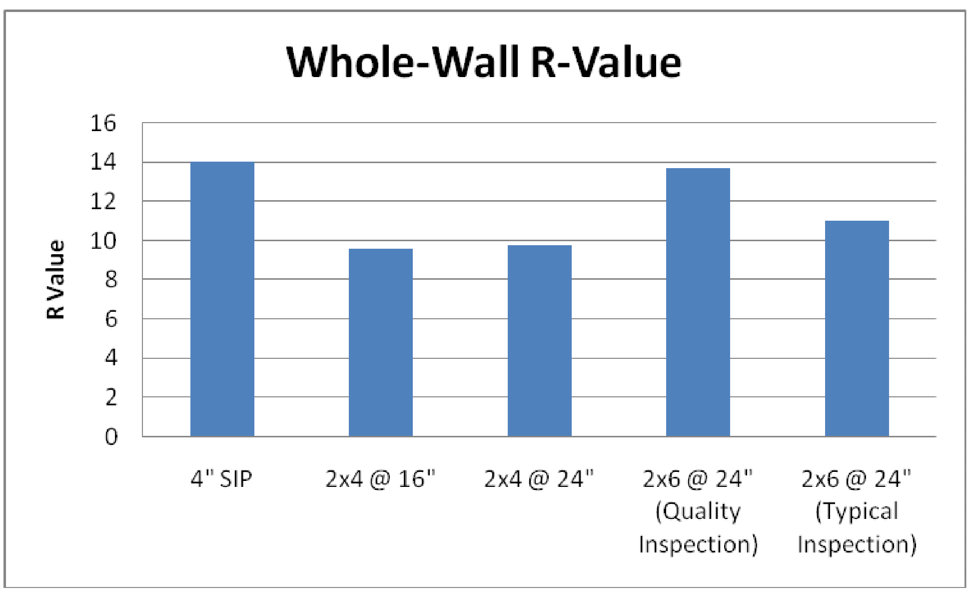

Figure 28 – Whole Wall R-Value Comparison [37]

[37] "SIPs Outperform Stick & Batt", SIPA. http://www.sips.org/content/technical/index.cfm?PageId=158

Tight Envelope/Increased Efficiency of HVAC/IAQ

SIPs also allow for exceptional indoor air quality. The degree of building tightness capable in SIP construction better enables mechanical ventilation to filter allergens and dehumidify air. This helps prevent mold problems, as mold and dust mites cannot survive in low-humidity environments. Also, the solid core insulation of SIPs is free of the voids, compressions, or thermal bypasses often associated with mold growth in wood frame, fiberglass-insulated construction.

Blower door testing conducted by the Oak Ridge National Lab has verified the tightness of SIP construction. A room with 4½ inch SIP walls, a SIP ceiling, a window, a door, pre-routed wiring chases, and electrical outlets showed 90% less air leakage than an otherwise identical room built with 2x6 studs, OSB sheathing, fiberglass insulation, and drywall. At 50 Pascals of negative pressure, the stick-built room leaked 126 cubic feet of air per minute (CFM), while the SIP room loss was a mere 9 CFM.[38]

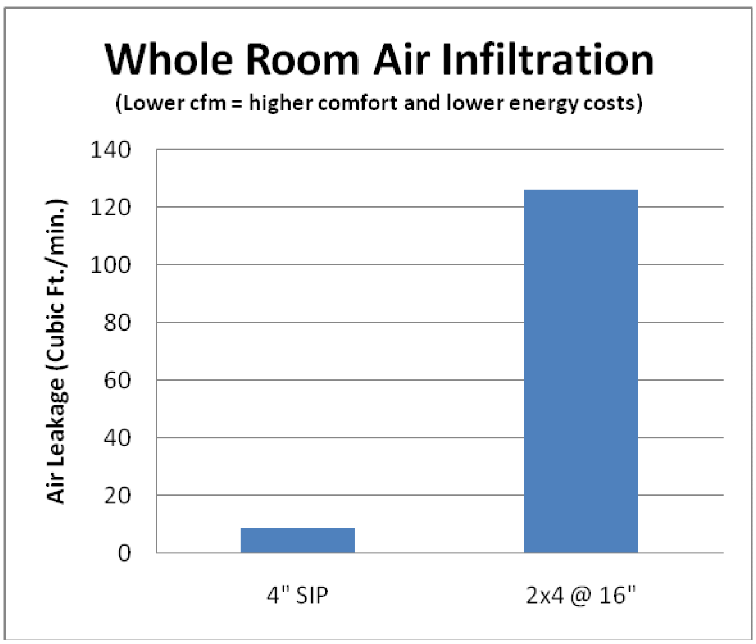

Figure 29 – Air Infiltration of SIPs Versus Wood Frame Construction [39]

The EPA has also recognized the exceptionally tight construction of SIPs through its ENERGY STAR rating system. Stick-built construction requires a pressurized blower door test to check the air tightness of a home. However, in December 2006, the EPA replaced the blower door test and energy modeling calculations normally required to meet ENERGY STAR qualifications with a visual inspection form for homes built with SIP walls and a SIP roof.[40]

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[38] http://www.epdsips.com/infopack/NewOakRidge.pdf
[39] http://www.epdsips.com/infopack/NewOakRidge.pdf
[40] SIPA news release 12/13/06, www.sips.org

This form requires inspection of all interior and exterior seams to ensure they are properly sealed with expanding foam or manufacturer-approved sealing mastic or tape to create an uninterrupted barrier between the two SIPs. The inspection must also check that dimensional lumber top-plates, bottom-plates, and end-plates are flush with the SIP core foam; that all through-wall penetrations such as HVAC duct work, electrical wiring, and plumbing have been sealed properly; and that scrap insulation has not been used to fill voids.[41]

2.3.2 – SIPs and LEED Certification

Currently, the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) program is the nationally accepted benchmark for the design, construction, and operation of high-performance green buildings. With environmental issues pushing themselves to the national forefront, this certification is increasingly sought after by builders and developers, and using SIPs in a building project contributes toward this recognition.

The LEED rating system awards points for meeting different energy and environmental criteria in areas such as building site, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and more. Points for the entire project are summed, and the project total falls into a tiered certification category (certified, silver, gold, and platinum certification). While this system of adding points is the general approach for LEED certification, it is further classified by building project type (new construction, renovation, etc.), and each classification has a separate set of evaluation criteria. Of these, LEED for New Construction (LEED-NC) is most applicable to SIPs.

Using SIPs in a LEED-NC construction project can also contribute significant points. There are sixty-nine potential points on the LEED-NC scale. Twenty-six points are required to be certified, thirty-three for silver, thirty-nine for gold, and fifty-two for platinum. Unlike the LEED for Homes checklist, SIPs are not referred to directly for new construction projects. However, the indirect gains achieved by using SIPs add up quickly. Up to ten points are possible for optimizing energy performance, based on a percentage improvement in the building performance rating compared to the baseline performance rating per ASHRAE/IESNA Standard 90.1-2004. While SIPs are not the only factor in a building's energy performance, they have been shown to improve energy efficiency by 35 to 50% compared to stick-built construction, making them a significant step towards these ten possible points. In addition, two points can be awarded if a project diverts 75% of material from disposal during construction. SIPs are fabricated to be the exact size necessary for a building project, and with walls and roofing making up a considerable percentage of a project's total construction material, using SIPs is a significant step towards the total of 75%. Two points can be earned if more than 20% of the project's building materials are manufactured within five hundred miles of the site. With SIP manufacturing facilities located throughout the country, using locally produced SIPs makes earning these two points relatively easy. Finally, SIPs can contribute up to two points in innovative design for exceptional performance and as an innovative material.

[41] EnergyStar SIP Visual Inspection form can be found at, www.energystar.gov

These potential points add up to a total of sixteen. While achieving certification is not as simple as meeting the minimum point value (there are several prerequisites for certification), using SIPs in a new construction project can indirectly contribute to as much as 60% of the total points needed for LEED Certification or 30% needed for LEED Platinum certification. Like LEED for Homes, using SIPs in your construction project makes a significant impact in gaining public credibility for your project as a sustainable building.

2.3.3 – Efficient Use of Material and Reduction of Construction Waste

In addition to being a main consumer of energy and electricity, buildings are responsible for the overuse of raw materials and the production of waste. According to a study by the Worldwatch Institute, buildings use 40% of the world's raw materials, adding up to three billion tons annually.[42] Of this high percentage, a staggering proportion ends up as construction waste.

The majority of this waste comes from building demolition and renovation, and the rest comes from new construction. In 1998, the EPA estimated that 136 million tons of building-related waste is generated in the United States annually, which is 25% to 40% of the national solid waste stream. A 2003 update showed an increase to 164 million tons annually, of which 9% is construction waste, 38% is renovation waste, and 53% is demolition debris.[43] Most of this waste goes into landfills, increasing the burden on landfill loading and operation. Much of this waste, such as chemically treated wood, can result in soil and water pollution.

Using CSIPs avoids much of the waste construction generates. SIPs are prefabricated in a factory, cut to the exact shape and size needed for the project. This minimizes the amount of excess material sent to a landfill, which is often up to 30% of material sent to a construction site. Also, many manufacturers recycle factory scrap to make other foam products, further maximizing the life of each piece and minimizing construction waste.

In addition to making less waste, CSIPs efficiently use material resources in their production. The insulation used in SIPs is a lightweight, rigid foam plastic composed of 98% air, and it requires only a small amount of petroleum to produce. The foam insulation used in panel cores is made using a non-CFC blowing agent that does not threaten the earth's ozone layer. In fact, in its first year, the average SIP home saves nineteen times the energy it took to make the EPS insulation.

2.3.4 – Life-Cycle Analysis

Building materials and their environmental impact should be considered over the full life of the building structure—also known as the building's "life cycle costs." To accomplish this, we must understand the total cost to the environment from material production, transportation, installation, use, and end of life reuse, recycling, or disposal. For this report, we will analyze the life cycle energy consumption (global

[42] Lenssen and Roodman, 1995, "Worldwatch Paper 124: A Building Revolution: How Ecology and Health Concerns are Transforming Construction," Worldwatch Institute.
[43] Construction Waste Management, Whole Building Design Guide, www.wbdg.org

warming potential, or GWP) and the cost of a standard CSIP (as a unit cost). Also, we will benchmark these results to alternative building technologies.

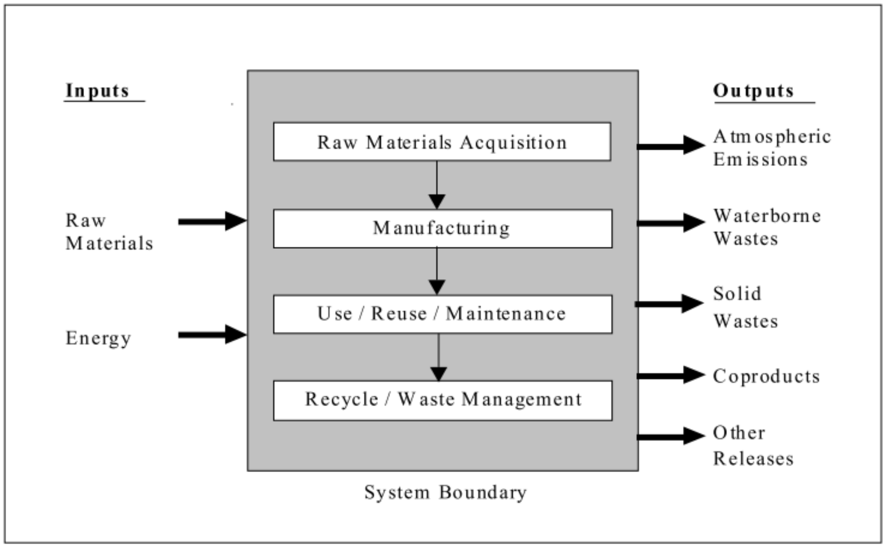


Figure 30 – Diagram of Life Cycle Stages [44]

The life cycle energy consumption, GWP, emissions were accounted for in the following categories:

A. Inputs:
   A.1. Raw material extraction and production of the raw materials and energy consumed.
B. System Boundary: energy consumed.
   B.1. Raw Materials Acquisition and Transport (including allotment of transportation of materials to fabrication of the CSIPs)
   B.2. CSIP Manufacturing (including fabrication of the CSIPs and allotment of transportation of the CSIPs to the building site)
   B.3. Building Use including:
      B.3.1. Construction of the CSIPs onto the building shell
      B.3.2. Energy consumed during use
      B.3.3. Embodied energy of maintenance and improvement
   B.4. Building Tear Down and Disposal:
      B.4.1. Demolition
      B.4.2. Transportation of material to landfill.
C. Outputs:
   C.1. Emissions
   C.2. Solid Wastes
   C.3. Co-products
   C.4. Other Releases

[44] Life Cycle Assessment: Principles and Practice," SAIC, EPA/600/R-06/060, May 2006.

Throughout this analysis, we will discuss potential options presented at each output category. Our hope is that one day, the industry will completely close the loop. The estimation is a relatively straightforward process given the nature of sandwich panels, which are comprised of only two constituent materials (fiber cement and EPS foam) and an adhesive. Because the adhesive is proprietary across each company, we have chosen to model the adhesive as a simple epoxy, which is considerably high in both energy and material resources. As such, we consider this estimation to be conservative.

Given the nature of CSIP manufacturing, we can easily estimate the system boundary and provide simple allotments for transportation. We have quantified the wastes and provide simple estimations and recommendations for maintenance, demolition, and alternative uses at the product's end use. All materials and metrics for energy used are derived solely or in part from two primary sources: the DEAM database by Ecobilan or the Athena database.

Given the CO_2 equivalent per panel, we can calculate the GWP following from "Environmental Life Cycle Assessment of Products…", published by the Centre of Environmental Science.[45] This "GWP factor" will be used throughout this life cycle analysis. To estimate the amount of specific greenhouse gases, multiply the GWP Factor by the calculated kg CO_2 equivalent/kg using the following chart:

Global Warming Gas	GWP Factor CO_2 = 1	Global Warming Gas	GWP Factor CO_2 = 1
Carbon Dioxide (CO_2):	1	CFC 12 (CF_2Cl_2):	7,100
Methane (CH_4):	56	CFC 13 (CF_3Cl):	11,000
Nitrous Oxide (N_2O):	280	CFC 14 (CF_4):	3,500
Halon 1301 (CF_3Br):	5,600	CFC 114 (C_2F_4Cl):	6,100
CFC 11 ($CFCl_3$):	4,500	HCFC 22 (CHF_2Cl):	4,200

Table 4 - Calculated Global Warming Potential Factors

In this report, CSIPs will only be represented as CO_2 equivalent per panel.

A. Inputs for raw material extraction, production, and energy utilized

Given the nature of fiber cement and EPS foam, or alternative foam if not using EPS, the LCAs of these products are known in commonly available life cycle material databases. Energy and GWP data for the constituent parts are as follows:

EPS – primarily polystyrene,	117 MJ/kg Primary Energy,	2.44 kg CO_2 equivalent/kg
CEMENT – primarily concrete,	9.5 MJ/kg Primary Energy,	1.19 kg CO_2 equivalent/kg
ADHESIVE – modeled as epoxy,	137 MJ/kg Primary Energy,	4.5 kg CO_2 equivalent/kg

Please note the $C0_2$ equivalency numbers for EPS and cement are modeled from aggregate data and may contain error. Therefore, we estimated component fabrication (the specific amount of energy and

[45] Heijungs, R. et al., "Environmental Life Cycle Assessment of Products…", Centre of Environmental Science, Leiden, Netherlands, 1992.

$C0_2$ in the production of expanded EPS from polystyrene and fiber-cement board). Further research is needed with the manufacturers of the component goods to determine exact numbers for the primary energy and CO_2 equivalent. The data integrity of this study hinges on the available data included in the referenced databases. Assuming one unit of CSIPs is comprised of approximately ½" FCB and 6" EPS (both conservative estimations), we find the ratio of EPS to cement, CSIP's energy and GWP data must be:

Basic Volume: Volume of raw materials per panel equals:

> Volume of EPS per panel = 1 (6" * 4' * 8') = 16.000 cubic feet per CSIP unit = 0.4531 m3
> Volume of FCB per panel = 2(.5" * 4' * 8') = 1.667 cubic feet per CSIP unit = 0.0755 m3
> Volume of ADHESIVE per panel = 2(4' * 8' * 0.005") = 0.03 cubic feet per CSIP unit = 8.5e-4 m3

Basic Weights: Given fiber-cement board density = 985 kg/m3, EPS Density = 16 kg/m3, and Adhesive = 970kg/m3 then the weight of raw materials per panel equals:

> Weight of EPS per panel = 0.4531 m3 * 16 kg/m3 = 7.25 kg
> Weight of FCB per panel = 0.0755 m3 * 985 kg/m3 = 74.4 kg
> Weight of ADHESIVE per panel = 8.5e-4 m3 * 970kg/m3 = .8245 kg

Total Weight of Panel (as a reference) = 7.25 kg + 74.4 kg + 0.8245 kg = 82.47 kg (or 182 lbs.)

Estimated Primary Energy and CO_2 Equivalency per panel: Therefore, the Primary and CO_2 equivalent per panel based on a weight analysis are:

> CSIP Primary Energy per panel = (100.3MJ/kg * 7.25 kg) + (1.6MJ/kg * 74.4 kg) + (137MJ/kg * 0.8245 kg) = 959.2 MJ
> CSIP $C0_2$ equivalent per panel= (2.1 kg CO_2/kg * 7.25 kg) + (0.2 kg CO_2/kg * 74.4 kg) + (4.5 kg CO_2/kg * 0.8245 kg) = 33.8 kg CO_2

B. System Boundary

CSIP Manufacturing assumes an allotment of transportation of materials to fabricate CSIPs, construction of the CSIP curtain wall, and an allotment of transportation of the CSIPs to the building site. To account for energy and material used in manufacturing and fabrication losses as well as additional waste used in construction losses, two factors must be provided:

- The efficiency factor in a manufacturing plant (assumed herein to be 85%, that is, a 15% loss in weight due to fabrication is provided)—accounted for in CSIP Manufacturing, and

- The efficiency losses during construction (assumed herein to be 5% given the nature of CSIPs (this estimation is solely based on in-field experience))—accounted for in Building Use.

Both of these factors need further analysis and should only be considered estimations; working with manufacturers of CSIPs, factors like the energy and equivalents of EPS and FCB can be determined more accurately.

Transportation allotments must be provided for both the raw materials and the finished products. These are variables given the distance of the CSIP fabricator to the raw materials and the distance of the CSIP fabricator to the construction site. We assume an average of both of these, and given the nature of these materials (EPS and FCB), we'll assume:

- the worst case of 400 miles (50% truck, 50% rail) for the raw materials, and
- 200 miles (100% truck) for the finished goods.

Truck and rail primary energy for this study will be based on Franklin Associates, LTD.[46] For this study, truck diesel is assumed to be 0.0017MJ/kg-mi and rail diesel is assumed to be 4.35e-4 MJ/kg-mi.

Raw Materials Acquisition and Transport: including allotment of transportation of materials to fabrication of the CSIPs

Raw Materials Acquisition has been accounted for in the above calculations for the panels; however, transportation must be calculated.

Truck = (200 mi.) * 0.0017MJ/kg-mi * 82.47 kg = 28.04 MJ
Rail = (200 mi.) * 4.35e-4MJ/kg-mi * 82.47 kg = 7.17 MJ
Total Transportation per panel = Truck + Rail = 28.04 MJ + 7.17 MJ = 35.21MJ

Given an estimation that the $C0_2$ equivalent is 0.08 kg $C0_2$ per MJ of diesel (multiple unverified sources), then:

Transportation $C0_2$ equivalent = 35.21MJ * 0.08 kg equivalent $C0_2$/MJ = 2.82 kg equivalent CO_2

CSIP Manufacturing: including fabrication of the CSIPs and allotment of transportation of the CSIPs to the building site.

Losses are accounted herein. As the panels are being fabricated, some material loss, damage, extras, and additional raw materials are needed for the finished goods. These losses are limited to additional energies and CO_2 equivalents and not weight because CSIPs are often fabricated with splines and additional materials, which would make up for any associated panel weight loss.

CSIP Primary Energy per panel = 959.2 MJ * (0.15 (loss in fabrication)) = 143.88 MJ
CSIP $C0_2$ equivalent per panel= 33.8 kg CO_2 * (0.15 (loss in fabrication)) = 5.07 kg CO_2

Therefore, the total transportation allotments are:

[46] Scot W. Horst and Wayne B. Trusty, "Integrating LCA Tools in LEED: First Steps."

Truck = (200 mi.) * 0.0017MJ/kg-mi * 82.47 kg = 28.04 MJ

Given estimation the $C0_2$ equivalent is .08 kg $C0_2$ per MJ of diesel (multiple unverified sources), then:

Transportation $C0_2$ equivalent = 28.04MJ * 0.08 kg equivalent $C0_2$/MJ = 2.24 kg equivalent CO_2

Building Use:

Construction of the CSIPs onto the building shell:

CSIP Primary Energy per panel = 959.2 MJ * (0.05 (loss in construction)) = 47.96 MJ
CSIP $C0_2$ equivalent per panel= 33.8 kg CO2 * (0.05 (loss in construction)) = 1.69 kg CO_2

Energy consumed during use: The energy in use will depend on the whole building energy analysis. For that reason, energy use for the building will be ignored for this analysis.

Embodied energy of maintenance and improvement: Building use includes energy consumed during use and the embodied energy of maintenance and improvement. An estimation of the embodied energy of maintenance and improvement for exterior goods, given a 50-year life, includes repainting at years 0, 7, 14, 21, 27, 35, 42, and 49 and interior repainting at years 0, 7, 14, 21, 27, 35, 42, and 49. It will be assumed that all of the repaintings will use latex with a known Primary Energy (70.8 MJ/kg) and CO_2 equivalent (0.8 kg $C0_2$/kg). Given a minimum thickness of paint per coat of 4 mils (1/250") and that each coat requires 2 applications, over the life of the building, 32 coats (2 sides * 2 coats * 8 times per 50 yrs. * 1/250" = 0.128") are applied, per unit panel, the weight of latex is defined by:

Volume of Latex per panel = 4'x8' * 0.128" = .34 cubic feet or 9.6e-3 cubic meters

Therefore, the Primary and CO_2 equivalent per panel are given assuming a 1185.4kg/m3 density of latex:

Painting CSIP Primary Energy per panel = 70.8 MJ/kg * (1185.4 kg/m3 * 9.6e-3m3) = 805.69 MJ
Painting CSIP $C0_2$ equivalent per panel= 0.8kg CO_2/kg * (1185.4 kg/m3 * 9.6e-3m3) = 9.1 kg CO_2

Building Tear Down and Disposal:
Building Tear Down assumes the energy consumed in the demolition and transportation of material to landfill.

Demolition: Building teardown will be assumed to be 50% efficiency based on panel fabrication. This is just an educated guess as no CSIP teardown has been performed to date.

CSIP Primary Energy per panel = 959.2 MJ * (0.5 loss in teardown) = 479.6 MJ
CSIP $C0_2$ equivalent per panel= 33.8 kg CO_2 * (0.5 loss in teardown) = 16.9 kg CO_2

Transportation of material to landfill: Transportation allotments must be provided for teardown and transport to the landfill. We'll assume for this study Transportation of 100 miles (100% truck). Using the same assumptions for truck and rail diesel, the total transportation allotments are:

Total Transportation per panel = 100mi * 0.0017MJ/kg-mi * 82.47 kg = 14.0 MJ

Given an estimation that the $C0_2$ equivalent is 0.08 kg $C0_2$ per MJ of diesel (multiple unverified sources), then:

Transportation $C0_2$ equivalent = 14.0 MJ * 0.08 kg equivalent $C0_2$/MJ = 1.1 kg equivalent CO_2

C. Outputs:

Emissions: Other than the emissions in the quantities listed below, the following are of a primary concern: 1) manufacturing of EPS must use expanded CO_2 as foaming agent and chemical additives for fire suppression, vector control (e.g., vermin, insects, etc.) and other additives are unknown; 2) Emissions from latex and the adhesives are unknown and not included herein; and 3) Emissions from tooling the EPS are unknown. The total $C0_2$ equivalents that must be considered are listed below in the summary.

Solid Wastes: Primary wastes are EPS, fiber cement, and miscellaneous application wastes including paints, adhesives, and application-related supplies. All of these wastes can be recycled into innovative, value-added forms like GEO-fill (combined EPS and FCB waste ground up and used as structural fill) or as plant growth media, including green roof growth medium (consisting of combined EPS and FCB waste ground up and used as a lightweight, highly absorptive growing medium). Some of these solid wastes can be considered co-products.

Co-products: Co-products are described above as solid wastes.

Other Releases: Other Releases are described above as emission outputs.

Summary of Inputs and Outputs:

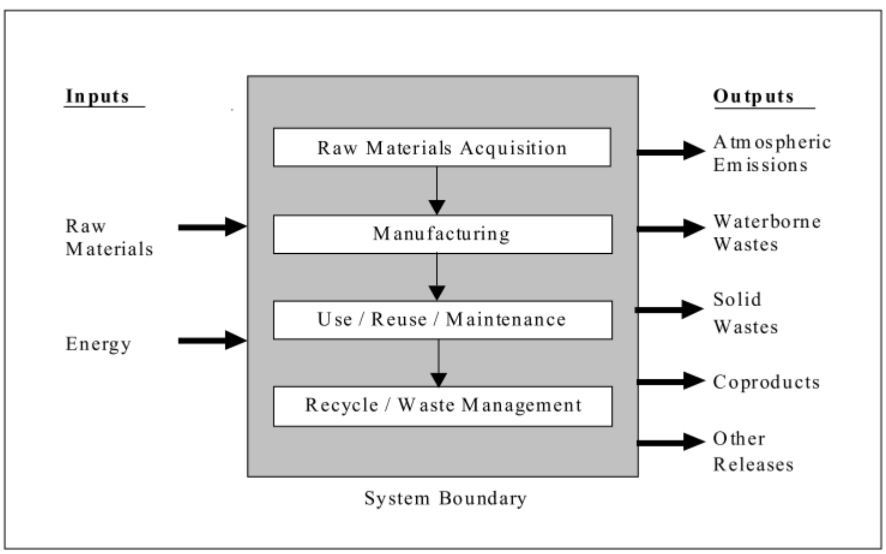


Figure 31 – Diagram of Life Cycle Stages [47]

[47] Life Cycle Assessment: Principles and Practice," SAIC, EPA/600/R-06/060, May 2006.

Description	Primary Energies (MJ)	Atmospheric CO2 Equivalents (kg)
Inputs (Raw Materials)	959.2	33.8
Transportation of Raw Materials	35.21	2.82
Fabrication	143.88	5.07
Transportation: Fabrication to Construct	28.04	2.24
Construction	47.96	1.69
Maintenance	805.69	9.1
Waste Management	479.6	16.9
Waste Management Transportation	14.0	1.1
Total	2513.58 MJ/Panel	72.72 kg CO_2 equivalent/panel (160 lbs.)
	78.55 MJ/sq. ft. of panel	2.27 kg CO_2 equivalent/panel (5 lbs.)
or	698.21 kWh/panel (21.82 kWh/sq. ft. @ \$0.10/kWh = \$2.18/sq. ft.)	

Table 5 – Summary of Calculated Primary Energies and Atmospheric CO2 Equivalents for CSIPs

3 – Multistory Design

While previous sections have focused on the performance aspects of individual panels and assemblies of panels, this section will explain the performance requirements of multistory buildings, building envelopes, and wall assemblies. This section will focus on how to optimize these performance variables and limitations for multistory buildings and will inform Section 4—a design guide for multistory applications.

3.1 – The Needs of a Multistory Building

The taller the building, the more complex the forces acting upon it are. Gravity systems must be able to channel the increased weight that comes with increased height safely to the foundation. Increased wind and lateral forces push and pull the building sideways, requiring more lateral bracing and structural consideration. Seismic forces also offer the possibility of larger lateral forces that must be resisted.

In addition, a multistory building must meet the more general requirements of all buildings:

Accessible	• Pertains to building elements, heights, and clearances implemented to address the specific needs of disabled people. o Provide equal access o Plan for flexibility: Be proactive
Aesthetics	• Pertains to the physical appearance and image of building elements and spaces as well as the integrated design process. o Engage the appropriate language and elements of design o Engage the integrated design process
Cost-Effective	• Pertains to selecting building elements on the basis of life-cycle costs (weighing options during concepts, design development, and value engineering) as well as basic cost estimating and budget control. o Utilize cost management throughout the planning, design, and development process o Use economic analysis to evaluate design alternatives Consider nonmonetary benefits such as aesthetics, historic preservation, security, and safety
Functional / Operational	• Pertains to functional programming—spatial needs and requirements, system performance as well as durability and efficient maintenance of building elements. o Account for functional needs o Ensure appropriate product/systems integration

Productive	• Pertains to occupants' well-being—physical and psychological comfort—including building elements such as air distribution, lighting, workspaces, systems, and technology.
	  ○ Integrate technological tools
	  ○ Assure reliable systems and spaces
	  ○ Design for the changing workplace
	  ○ Promote health and well-being
	  ○ Provide comfortable environments

Secure / Safe	• Pertains to the physical protection of occupants and assets from man-made and natural hazards.
	  ○ Plan for fire protection
	  ○ Ensure occupant safety and health
	  ○ Resist natural hazards
	  ○ Provide security for building occupants and assets

Sustainable	• Pertains to environmental performance of building elements and strategies.
	  ○ Optimize site potential
	  ○ Optimize energy use
	  ○ Protect and conserve water
	  ○ Use environmentally preferable products
	  ○ Enhance indoor environmental quality (IEQ)

Table 6 – General Building Requirements

Developments in structural systems and building envelopes have occurred in the pursuit of a more optimized approach to these requirements. Different individual parts evolved to handle the individual performance requirements. The layered construction, for example, includes layers for insulation, moisture control, soundproofing, durability, structure, and on and on.

The result of this process is different materials achieve each performance requirement, with each material performing a separate function. For example, the air barrier may simply be a coating on a support layer. While this separation ensures that each performance criteria may be met, it may not be ideal or optimized.

What if it were possible to meet all of these criteria with one composite assembly? This would drastically simplify the building envelope and wall assembly, making for easier construction and design and minimize reliance upon an interrelated, complicated system of parts.

CSIPs can perform these functions as a single, factory fabricated assembly, removing the complexity thought inherent in the modern wall assembly. This section will elaborate on this concept, examining common wall assembly types, their performance attributes, and how CSIPs might be used.

3.2 – The Functions of Building Envelope and Wall Assemblies

Buildings dynamically respond to the larger environment. Walls help control and filter the interior and exterior environments, performing the following basic functions:

1. Providing structural supports if a bearing wall
2. Providing structural support for wind loading as a bearing wall and as curtain walls
3. Acting as a protective enclosure from the elements as waterproofing and weather barriers
4. Allowing for openings for vision and vent and
5. Serving as a filter between the inside and outside for flow of heat, light, air, moisture, dirt, sound, people, as air and moisture barriers.

A wall's functions primarily depend on the wall system used. Wall panels are more robust than curtain walls, as they act as the building's primary structural component. Curtain walls typically offer a better thermal control mechanism (in their ability to include more unbroken areas of insulation) and allow for alternative construction administration methods to deliver whole buildings more cost effectively. For example, the precast concrete industry has developed manufactured wall panels that can leverage the curtain wall benefits in large scale precast wall panels. These functions of walls, other than structural, are primarily as a filter or barrier to control the movement of variables into and out of the building as an envelope.

The primary function of envelopes is to withstand the elements by controlling the ability of rain, dirt, fire, noise, and insects to enter the interior. The secondary function of envelopes is to control passage between the interior and exterior. This control measure includes temperature (thermal transfer and losses), ventilation, light, and air infiltration. Additionally, the envelope controls the passage of interior vapors, humidity, and air to the exterior. Envelopes act as weather barriers (to prevent rain from entering the interior), vapor barriers (to control water vapor penetration into and out of the building and condensation), and air barriers (to control the movement of air, or unknown infiltration points, into and out of the building). A tertiary function of envelopes is to prevent access or entry into building through doors and windows (this function is not a focus of this report).

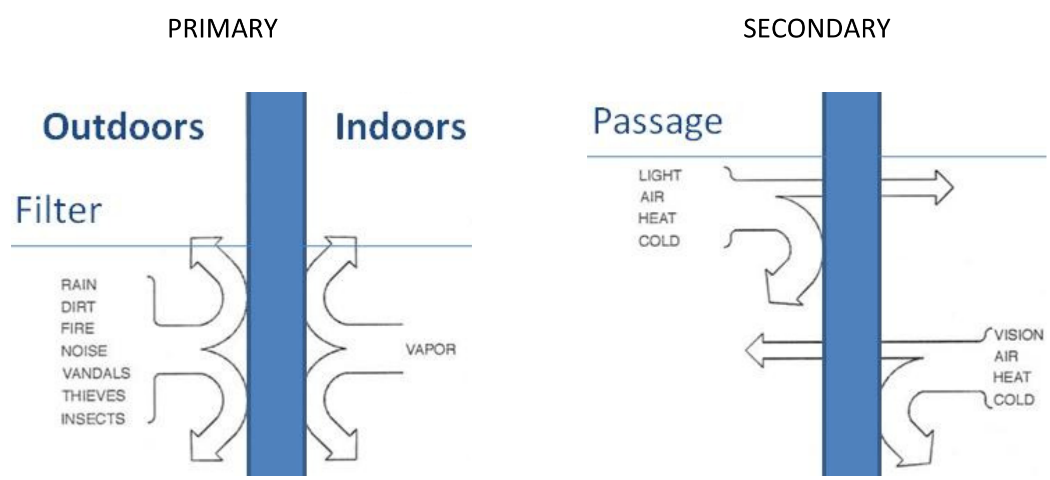


Figure 32 – Primary and Secondary Functions of the Building Envelope

3.2.1 – Weather Barriers: Understanding Waterproofing Control Measures

A weather barrier is neither an air barrier or vapor retarder; rather, it is a liquid moisture-resistant layer to protect the building from the elements. Weather barriers protect construction from damage due to precipitation and wind-driven rain. Weather barriers are "water-resistive barriers" in the International Building Code (1404.2), which requires a minimum of one layer of No. 15 asphalt felt behind the exterior wall veneer, unless other conditions are met or equivalency is demonstrated.

Waterproofing is best controlled through proper detailing of assemblies to ensure water has an unbroken barrier to escape any joint, infiltration area, or crack in the system. Water penetration resistance is a function of substructure construction, drainage details, water management control (weather stripping, gaskets, and sealants), and flashing/counter-flashing of all windows, penetration, and so forth

To understand the design issues, first we must discuss the mechanisms that move water into the building: gravity, kinetic energy, pressure gradients, surface tensions, and capillary action. Because CSIP wall units are built up from monolithic sandwich panels, more perimeter lengths must be properly designed, detailed, and constructed to ensure proper water management and water shed to the building's exterior. This allows the designer to be cautious and conservative about water management details while focusing on the main concern of water management between units and at unit corners.

Typically, the parts and pieces (including the individual panels) that make up larger wall units must be detailed to prevent water infiltration. Some of the individual details of CSIPs have been discussed in previous chapters. However, leveraging these industry standards, designers will be required to provide weatherization details by the following steps:

A. Installation of the CSIPs into wall units:
    1. Installed CSIPs,
    2. Apply Latex Caulk at CSIP joints, and
    3. Apply CMU Block Fill to the entire CSIP assembly.
B. Installation of multiple wall units together:
    4. Apply caulk within the interior cavity between installed wall units,
    5. Tool caulk in cavity to correctly apply to surfaces, and
    6. Install gasket seal and provide weeps/pressure equalization points.

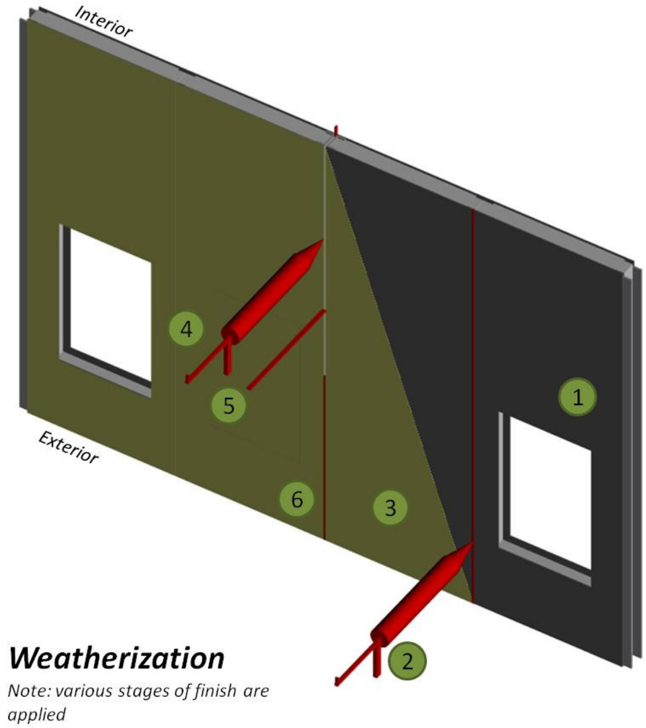


Figure 33 – Required Steps for Weatherizing CSIPs

All joints and boundary conditions between wall units should be treated like pressure-equalized cavities.

A pressure-equalized cavity is a concept made common in pressure-equalized rain screens. Pressure-equalized rain screens integrate a porous exterior cladding and compartmentalized air spaces with generous ventilation to an interior watertight, airtight support wall. Pressure equalization controls the pressure differential across the cladding systems magnified by winds and controls wind-driven rain. This control measure effectively eliminates the remaining pressure forces affecting rain screens that drive rain into the interior by using barriers to compartmentalize the air cavity as a pressure-equalized cavity, thereby allowing rapid air pressure equalization and minimal moisture intrusion.

Adapting these details to wall units will involve the backmost interior surface to be sealed (illustrated below as (5)) to form a cavity between the inner and outer surface that is allowed to vent while still allowing positive drainage to the exterior; the outer cavity is maintained by the installation of a gasket seal with weeps (illustrated below as (6)).

Permeability

This approach to weatherization is based on an understanding of the permeability of the wall assembly and components. This approach includes how water is transmitted into and out of the assembly given weather, pressure, and vapor transmission. Additionally, the drying mechanism through temperature, direct sunlight, and differences in relative humidity must be leveraged. Therefore, we must diagram a simple SIP wall and determine what limitations must be understood.

To accomplish this task, we must break down a SIP wall into its installed constituents and determine the permeability of each material (in perm-inch):

Exterior Finish	Fiber Cement Board	EPS (at 5.5”)	Fiber Cement Board	Interior Finish
3.5 to 6.1	*1.5*	*.5 to .6*	*1.5*	*3.5 to 6.1*

From this diagram, we can determine where water will sit depending on how impermeable each neighboring constituent part is. For example, if a material is highly permeable but is neighboring a component that is not, water can easily pass through the highly permeable material and will effectively be impeded or “stopped” by the impermeable material. With CSIPs, particularly because there are no additional moisture management layers like pressurized rain screens or cavity walls, the constituents on a material level must help the system manage water vapor and transmission. This necessity translates into properly allowing water to dry out of the assembly. Therefore, the center core must be the lowest permeability with the constituent layers being of a higher permeability—this arrangement will allow drying to the exterior and interior away from the core.

Exterior Finish	Fiber Cement Board	EPS (at 5.5”)	Fiber Cement Board	Interior Finish
3.5 to 6.1	*> 1.5*	*> .5 to .6*	*< 1.5*	*< 3.5 to 6.1*

Or, to illustrate moisture drive:

Exterior Finish	Fiber Cement Board	EPS (at 5.5”)	Fiber Cement Board	Interior Finish
3.5 to 6.1	*←1.5*	*← .5 to .6 →*	*1.5 →*	*3.5 to 6.1*

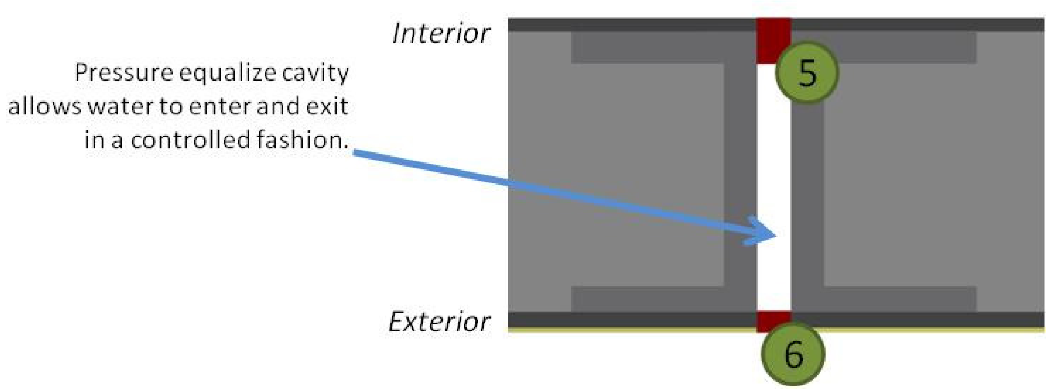


Figure 34 – Pressure Equalized Cavity

Tests for weather barriers are required based on ASTM E331-00 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure

Difference, which allows CSIPs to show conformance to 1403.2 as a weather barrier resistant to water intrusion and vapor permeance to allow drying while reducing vapor intrusion. Additional tests for weather barriers on whole curtain walls may be required, including:

i. ASTM E331-00 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference,
ii. ASTM E547-00 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference, and
iii. AAMA 501-4 Dynamic Rain Penetration Test (may be required).

3.2.2 – Thermal Barriers: Understanding Thermal Control Measures

The energy-saving potential of building with CSIPs is the most apparent sustainable advantage of utilizing CSIPs as wall units. A CSIP building envelope provides high levels of insulation and is extremely airtight. This means significantly lower operating costs for an owner, as well as a smaller contribution to the energy use and carbon emissions from your building.

Energy flow through building panels and wall assemblies is primarily driven through two mechanisms:

1) Temperature-driven heat transfer: Temperature-driven heat transfer is the differential between the inside and outside temperature—heat is either lost or gained through the section, frame, and panels. This is indicated in terms of the U-factor or R-factor of the assembly (U=1/R). Heat transfer is driven by three mechanisms:
   a. Conduction is the heat traveling through a solid material,
   b. Convection is the transfer of heat by the movement of gases or liquids through a system, and
   c. Radiative heat transfer is the movement of heat energy through space without relying on conduction through the air or by movement of air.
2) Infiltration: Infiltration of heat lost or gained through the air infiltration through cracks in the assembly. This negative effect is measured in terms of the amount of air that passes through a unit area of the panel product under different pressure conditions. Infiltration is thus driven by wind-driven and temperature-driven pressure changes and fluctuations. Infiltration may also contribute to interior humidity.

The following panel areas must be optimized to use CSIPs as an effective envelope system (illustrated below):

- Baseline panel by optimizing the CSIP thickness,
- Substructure joints by examining the CSIP to curtain wall unit boundaries and curtain wall units interaction and connections,
- Spline joints by optimizing CSIP to CSIP connection, and
- Penetration joints by optimizing the CSIP to penetrating unit connections (such as windows).

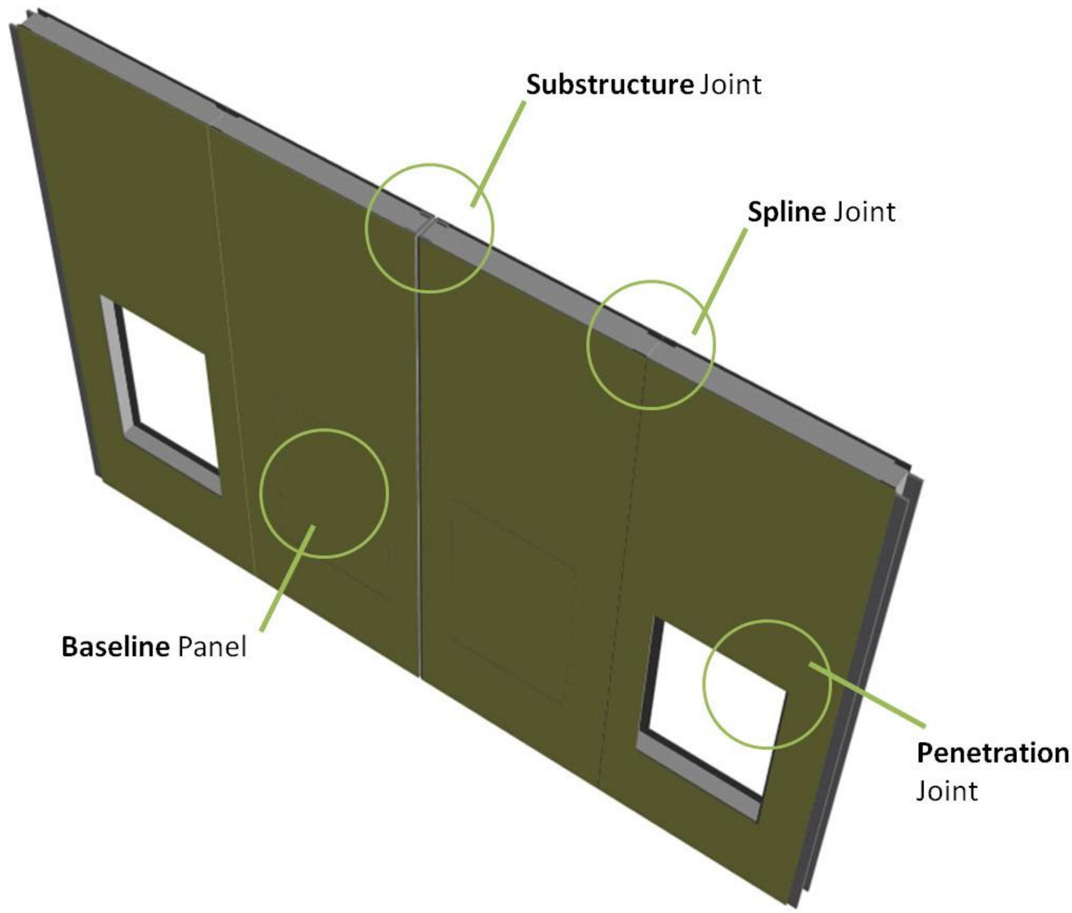


Figure 35 – Typical Joint Locations for Thermal Optimization

For a discussion of panel optimization and how heat transfers through CSIPs, refer to Section 2.3.1. Note that each manufacturer and project will have specific details that require selection, analysis, modeling, and optimization, and it is recommended designers discuss this with the panel manufacturers.

3.2.3 – Air Barriers: Understanding Infiltration Control Measures

Air barriers retard air passage and may be vapor-permeable (to allow condensation movement), but they are liquid moisture-resistant. Air barriers offered are typically mechanically fastened sheets (i.e., "housewraps") and spray- or roller-applied coatings (i.e., “fills” like block fill for CMU construction). An air barrier may also function as a water-resistive weather barrier.

Factors that affect building tightness are the interior seals, caulks, and other treatment of interior finishes, trim, and interactions between the two that close gaps, cracks, and imperfections in the construction forming the air barrier. Typically air infiltration is a surface control measure that paint and caulk may control.

There is no easy way to calculate and design for building tightness prior to final finish because it ultimately relies on the specifications and quality of installation. The tightness is ultimately determined by the seals between the panels, the panels to the building, and all the penetrations that can be evaluated after the building is constructed through similar testing methods as the blower door test. Building tightness hinges on the weather barrier test for the panel systems, and basing the assumptions on physical tests, mock ups, and prototypes. Additionally, building tightness is determined by the seals and expansion and contraction of unit-to-unit interaction.

Penetrations through the envelope are key areas in which air infiltration is controlled. The proper use of flashing and counter-flashing can minimize air infiltration, as well as properly installing window units and preparing openings and penetration for controlled passage. The installation of windows into the panels is outside the scope of this document, as it is clearly manufacturer-specific, but each penetration should be prepped with an elastomeric pan flashing, jamb flashing, and header flashing followed by the installation of the window with proper sealants and mechanical fastening to the blocking in the CSIP. These details may require windows with exterior flanges, but they promote proper drainage and evacuation of water to the exterior. Counter-flashing should be installed, and as required, materials to create and maintain a drainage cavity should be installed between the counter-flashing and exterior window trim. These layers of redundancy and control allow localized drainage cavities to be built up around penetrations while relying on the flashing materials to channel excess water to the exterior. Any moisture saturated in the wall assembly can dry out given that the exterior and interior facing materials should be more permeable than the interior core material. Typical window and wall details for penetrations are illustrated in Sections 1.5.2 and 3.6, but they have so far been limited to residential construction.

Tests for air barriers are required based on air leakage, ASTM E283 - 04 Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen.

3.2.4 – Cautionary Note on CSIPs

Vapor retarders, mentioned above, restrict passage of both air and water vapor and perform similar tasks as combined water and air barriers. Vapor retarders are often mechanically fastened sheets, self-adhesive sheets, mastic, and spray coatings.

Vapor moisture management is less of an issue with closed wall panels like CSIPs if the facing materials are more permeable than the core material. This management principle will allow any water to dry out of the core material (and more importantly the lamination line). Therefore, the designer should be concerned with the perm ratings of all facing materials and exterior finishes. As long as the perm rating of the facings is less than that of the core, condensation control may not be required.

However, using permeance as the means of vapor retardation for CSIP curtain wall units may only be effective in climates with an annual precipitation of less than 60 inches and in climates that have few degree heating days to allow for moisture evacuation. The effects of this control measure and determining which climate zones are suitable for CSIPs are outlined below.

These are areas that require future research for the industry. The manufacturer should be consulted for technical information and interpretations of vapor and condensation management.

3.2.5 – Determining CSIP's Candidate Climate Zone

If CSIPs are to be used without exterior weather barriers, protection, and finishing (as recommended in this report), they should be limited to climate zones that will promote positive drying to the exterior (assuming the core is less permeable than the faces to promote proper drying action) and less than excessive amounts of rain (to allow time to promote drying). Additionally, because little data exists on freeze-thaw cycles, CSIPs should be limited in areas without excessive frost, freezing, and degree heating days. From the following sets of data, the candidate thermal zones will be identified.

1. Degree Heating Days (degrees F), adapted from National Weather Service and the National Climatic Data Center. The value shown is the number of degrees over a year the average temperature departs from human comfort. Therefore, in the map below, a high degree heating day translates into more cold weather annually. Because of the aforementioned unknowns with CSIPs, this data should be considered the initial starting point when determining candidate climate zones. CSIPs need a climate with the smallest degree heating days to prevent freeze-thaw issues and potential damage to the structure (as explained in Section 2.2.1.2).

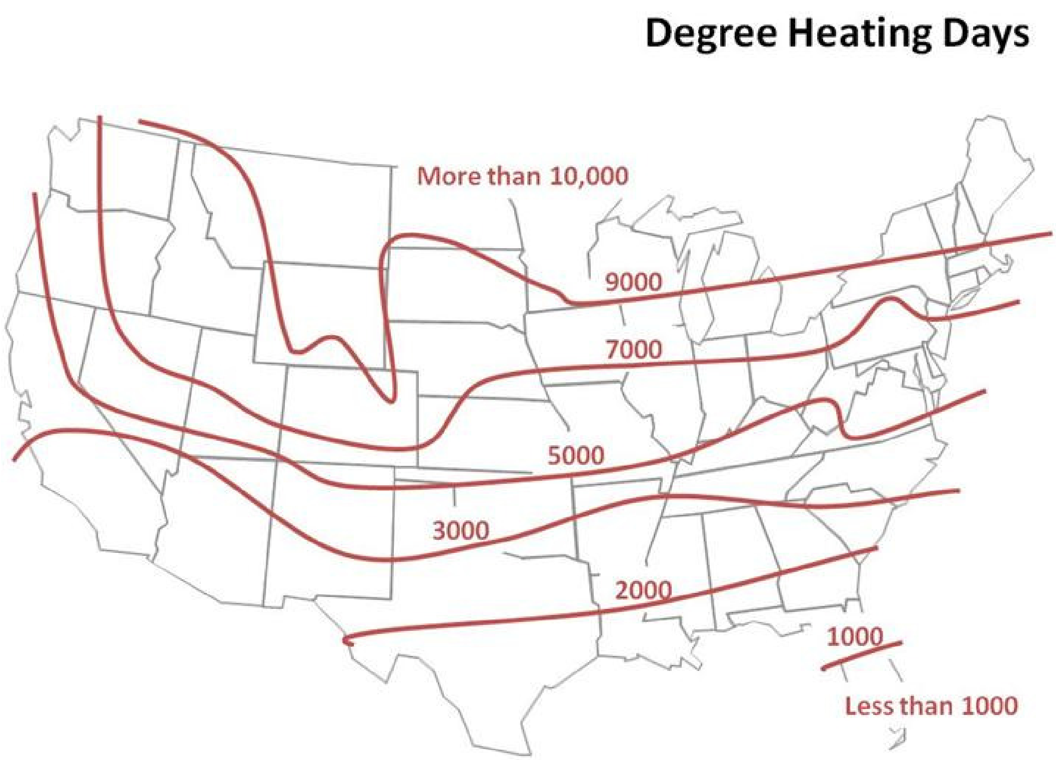


Figure 36 - Degree Heating Days

2. Annual Average Rainfall (inches), adapted from National Oceanic and Atmospheric Association. Because CSIPs, and more importantly, the fiber-cement facings are penalized structurally when wet (a discount factor is applied), annual rainfall must be examined. The candidate climate zone must get a small amount of annual rainfall, or the structure will be weakened for a large duration of the building's use. CSIPs have a natural ability to dry out, particularly when the inner core is less permeable to water than the outer facings (meaning water can freely move into and out of the EPS foam); however, the CSIP needs a mechanism to drive that water out, be it sunlight, temperature, or air movement.

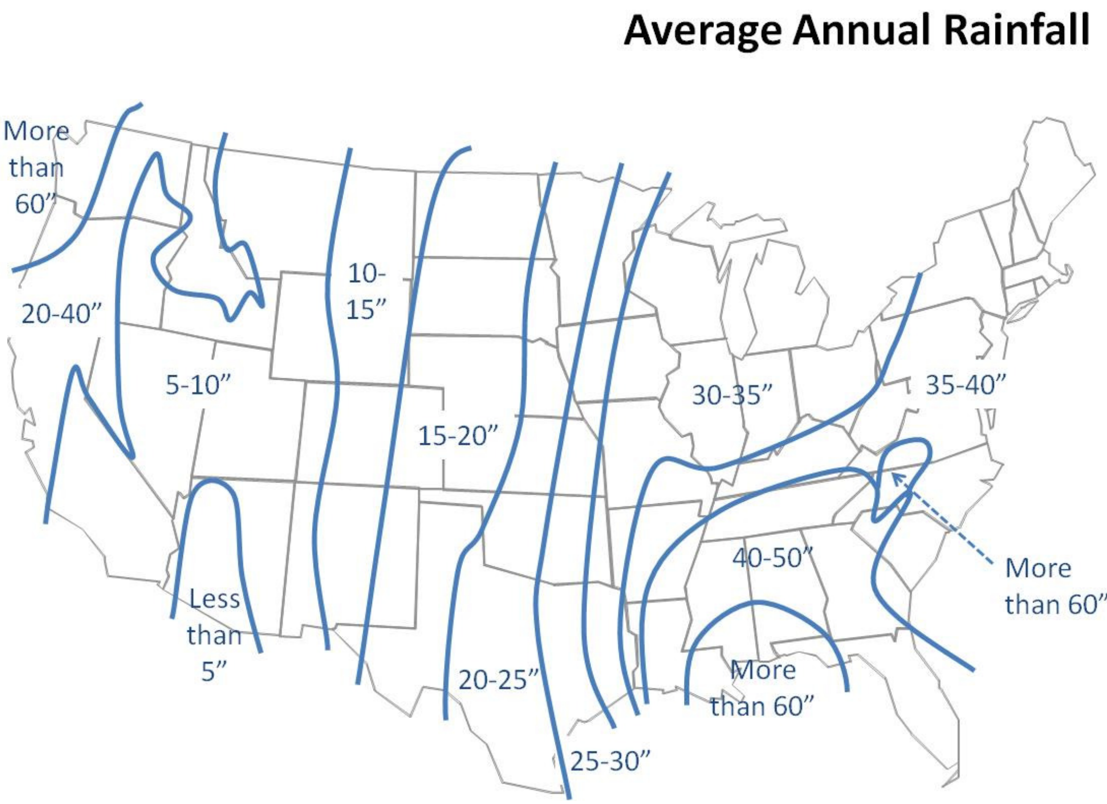


Figure 37 - Average Annual Rainfall

3. Climate Zones, adapted from DOE's Building America. Furthermore, we must understand the climate conditions the CSIPs may be subject to. To examine these different climate zones, we can evaluate the DOE's definitions and boundaries to find a candidate that provides sunlight, temperature, and air movement. The DOE has defined the different zones as:
    a. "Hot-Humid: A hot-humid climate is generally defined as a region that receives more than 20 in. (50 cm) of annual precipitation and where one or both of the following occur: A 67°F (19.5°C) or higher wet bulb temperature for 3,000 or more hours during the warmest 6 consecutive months of the year; or a 73°F (23°C) or higher wet bulb temperature for 1,500 or more hours during the warmest 6 consecutive months of the year.
    b. Mixed-Humid: A mixed-humid climate is generally defined as a region that receives more than 20 in. (50 cm) of annual precipitation, has approximately 5,400 heating degree days (65°F basis) or fewer, and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months.
    c. Hot-Dry: A hot-dry climate is generally defined as a region that receives less than 20 in. (50 cm) of annual precipitation and where the monthly average outdoor temperature remains above 45°F (7°C) throughout the year.
    d. Mixed-Dry: A mixed-dry climate is generally defined as a region that receives less than 20 in. (50 cm) of annual precipitation, has approximately 5,400 heating degree days (50°F basis) or less, and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months.
    e. Cold: A cold climate is generally defined as a region with approximately 5,400 heating degree days (65°F basis) or more and fewer than approximately 9,000 heating degree days (65°F basis).
    f. Very-Cold: A very cold climate is generally defined as a region with approximately 9,000 heating degree days (65°F basis) or more and fewer than approximately 12,600 heating degree days (65°F basis).
    g. Subarctic: A subarctic climate is generally defined as a region with approximately 12,600 heating degree days (65° basis) or more.
    h. Marine: A marine climate is generally defined as a region that meets all of the following criteria: A mean temperature of coldest month between 27°F (-3°C) and 65°F (18°C); A warmest month mean of less than 72°F (22°C); At least 4 months with mean temperatures more than 50°F (10°C); A dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere.

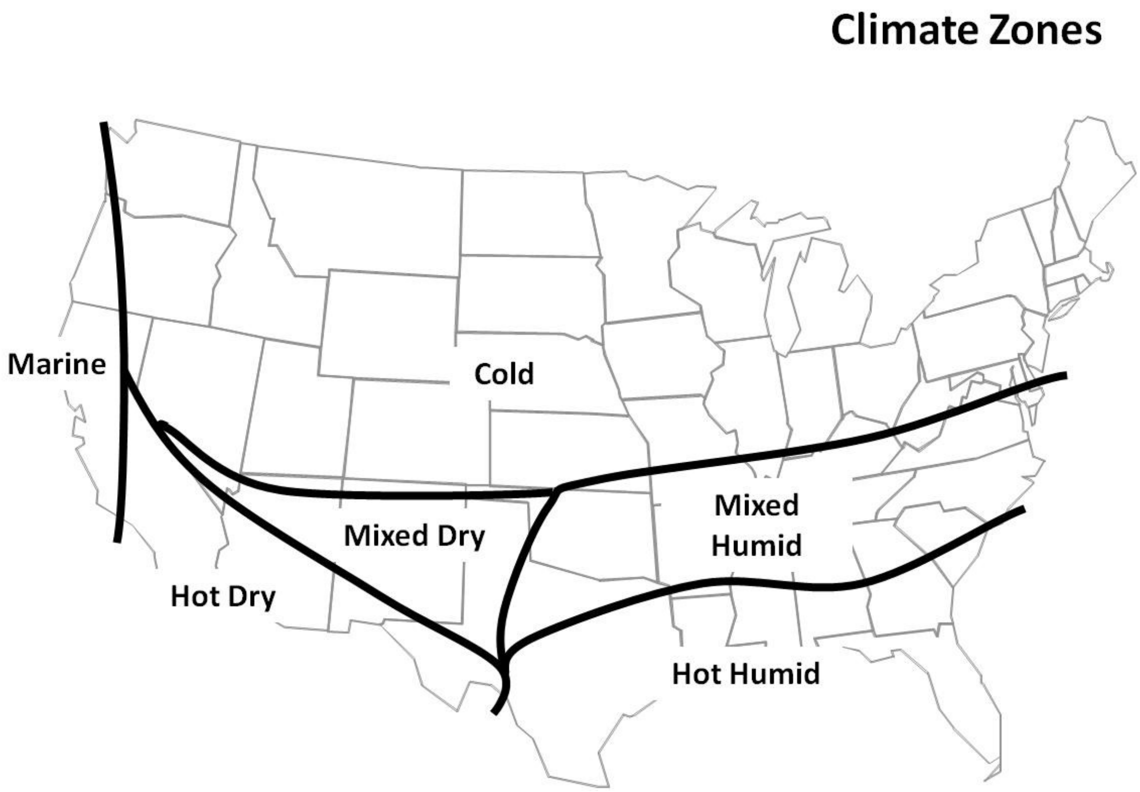


Figure 38 - Climate Zones

4. Composite Analysis–"Putting it all together." To render a decision on good candidate CSIP climate zones, all of the aforementioned concerns and data points must be synthesized into a singular map. From this synthesized map, a marketing map can be generated. Three different zones are presented: Good, Average, and Poor.
    i. Good: Good represents areas that have a low chance of freezing, little annual rainfall, and plenty of action to dry the assembly out. These areas represent most of the United States below the Mason-Dixon Line and large areas of the West, South, and Southeast.
    j. Average: Average represents areas that may have too much rain but few degree heating days so the assemblies have plenty of time to dry out. This is a risk local manufacturers must consider.
    k. Poor: Poor represents areas that have too much rain or too many degree heating days, which may promote structural weakening or chances of freeze-thaw damage.

    Hot-humid climates will show up as poor zones, but these are areas where CSIPs may perform very well because of the excessively low degree heating days and local weather factors where most of the rain falls over short durations, so there may be little chance for the walls to get excessively wet.

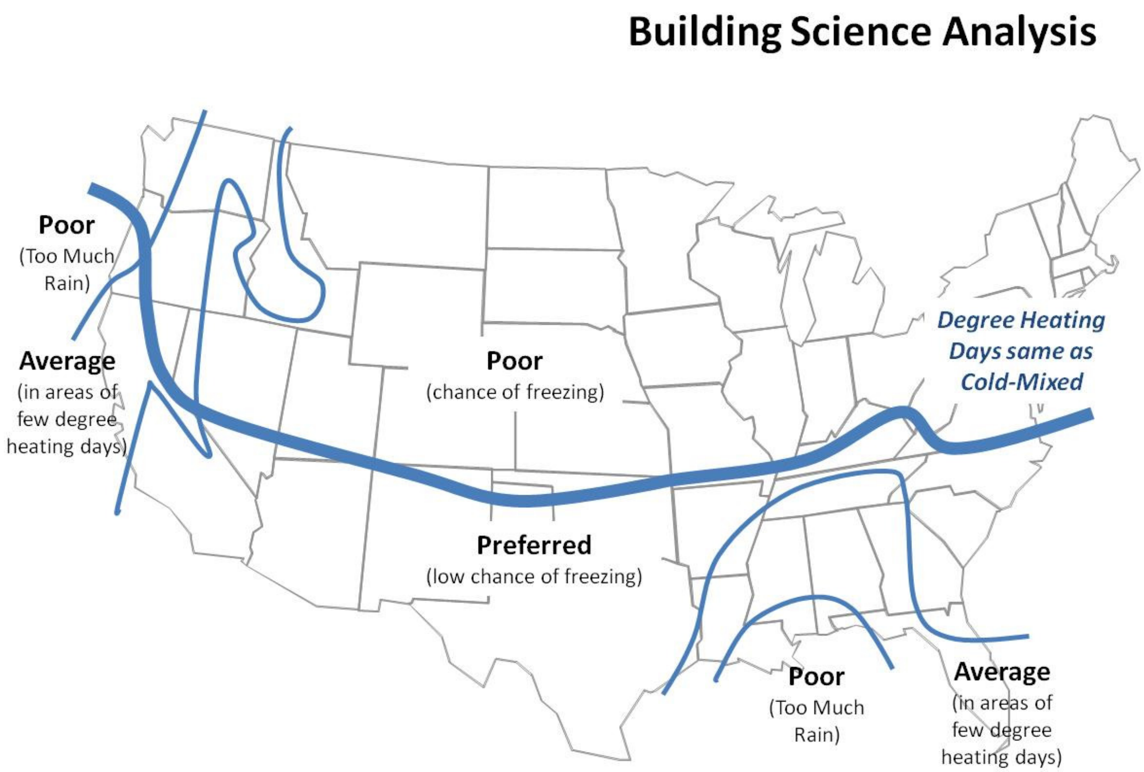


Figure 39 - Building Science Analysis

5. Markets, based on stratum climates (U.S. Forestry Service). After identifying target climate zones, it is easy to compare the candidate climate zones with the existing SIP market. First, 50% of the market is above the Mason-Dixon Line and 50% is below. Therefore, CSIPs will already be competing in markets where SIP manufacturers have been cultivating business. Second, we can compare the type of markets these SIPs traditionally make up (between residential and commercial). And thirdly, we can quantify the total size of the market based on existing SIP sales. Therefore, we can generate four preferred markets:

    l. Coastal (SE): existing SIP market making up 19% of all SIP sales; mostly residential but some commercial; target opportunity to sell CSIPs over SIPs on their material and cost advantages and grow the commercial industry for low- to high-volume sales.
    m. South: existing SIP market making up 10% of all SIP sales; predominately residential; target opportunity to sell CSIPs over SIPs on their material and cost advantages and start the commercial industry.
    n. West: existing SIP market making up 10% of all SIP sales; residential and commercial; target opportunity to sell CSIPs over SIPs on their material and cost advantages and start the commercial industry.
    o. Southwest: existing SIP market making up approximately 10% of all SIP sales; predominately residential; target opportunity to sell CSIPs over SIPs on their material and cost advantages and start the commercial industry.

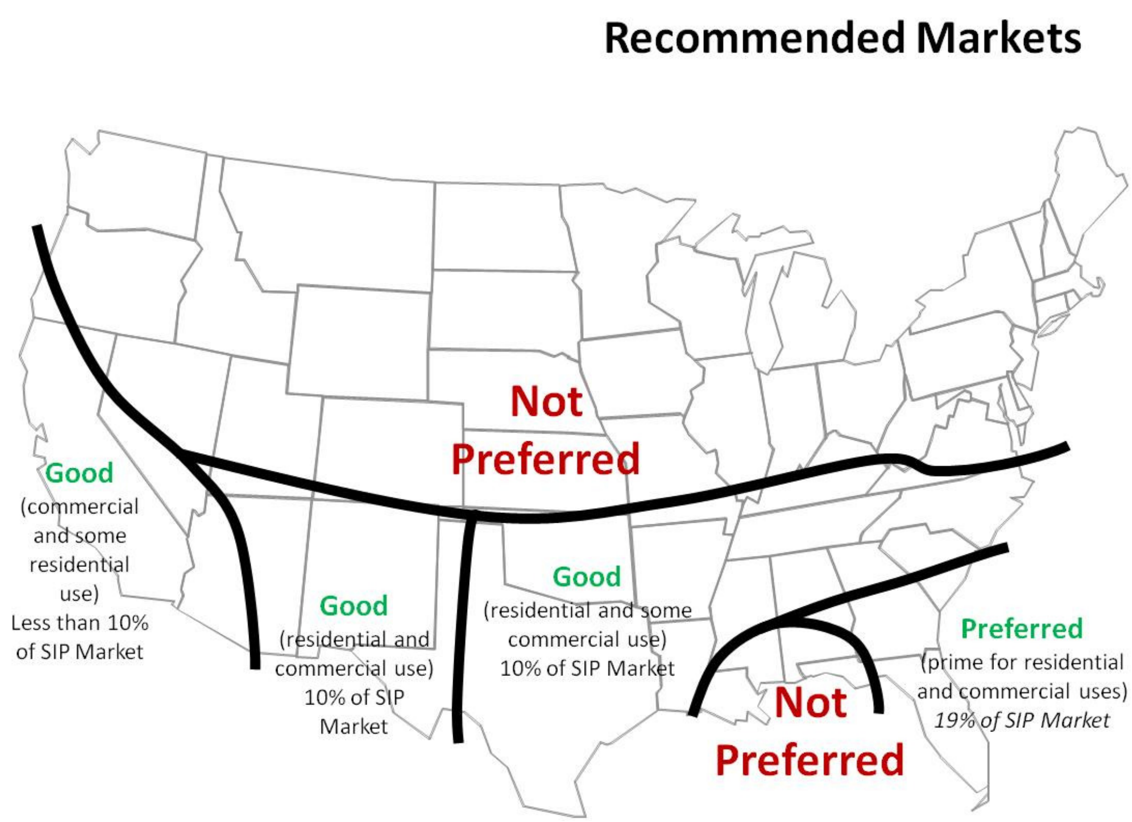


Figure 40 - Recommended Markets

This is not a steadfast rule and should not be taken as such. However, if CSIPs are to be used in areas beyond the recommended scope here, it is highly suggested a different weatherization/vapor barrier strategy be used.

3.3 – Possible Uses of Panels in Multistory Building Envelope Systems

Prefabricated wall panels (such as CSIPs), can be used to simplify construction, optimize performance, and reduce costs in multistory building systems. There are two major candidate methods for CSIPs in which wall panels can be used: load-bearing element systems and non-load-bearing systems.

3.3.1 – Load-Bearing Panel Systems

Building envelope wall panels that act as a building's load-bearing structural elements are a structurally and economically efficient way of transferring loads to the building foundation. These panels become an integral part of the structure, taking vertical and horizontal floor and roof loads, and/or transferring horizontal loads into shear walls or service cores.

The increased cost of load-bearing wall panels (due to reinforcement and connection requirements) is typically offset by the elimination of a separate perimeter structural frame. This can also result in a reduction or elimination of the need for a structural core or interior shear walls (especially in a building with a large wall-to-floor ratio). These cost-savings tend to be the greatest in low- to mid-rise structures of three to ten stories.[48]

3.3.2 – Non-load-bearing Panel Systems

Non-load-bearing walls carry only their own weight and are used to close in a steel or concrete frame building. The most common type of non-load-bearing building envelope type is a curtain wall. While curtain walls are typically thought of as light enclosures of glass, they can be made of many different materials, such as metal panels or thin stone. The framing is attached to the building structure and does not carry the floor or roof loads of the building. Wind and gravity loads of the curtain wall are transferred to the building structure, typically at the floor line.

3.3.3 – Suitable Design System Candidates

Currently, the application of CSIPs to buildings is primarily limited due to codes. Fire codes mandate that a building's structural members must be non-combustible construction, as determined by ASTM E136 - 04 Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C and ISO 1182 Non-Combustibility Test for Building Materials. In each of these tests, multiple specimens must survive without substantial mass loss for the specimen to be considered non-combustible. ASTM E136 and ISO 1182 are both severe tests.

[48] Freedman, Sidney. "Loadbearing Architectural Precast Concrete Wall Panels". Pg 93.

No SIP material utilizing cores of polystyrene or polyurethane could survive 750°C and these severe tests. For that reason, CSIPs are considered combustible construction and are limited for structural uses to Type V construction. For this reason, CSIPs cannot be used as load-bearing panels in multistory construction.[49]

However, SIPs can be used as exterior wall coverings in Type I buildings per 603.1.10 of the IBC. As such, SIPs can be used as exterior wall envelopes in non-load-bearing circumstances so long as they demonstrate with testing they are weather barriers to protect and manage water infiltration.

With that in mind, the applicability of CSIPs to multistory buildings is as a curtain wall system. The purpose of this report is to determine candidate buildings types and limitations for the applicability of CSIPs to multistory construction. This application will be based on curtain walls given the aforementioned limitations. Curtain walls can be built in any building of any height given a substructure that carries the superimposed vertical loads of the building.

3.4 – Classifications of Curtain Wall Systems

There are five common curtain wall systems and related installation methods. Before finding a candidate system for CSIPs, the five systems will be explained and illustrated. Additionally, applicability of each system to CSIPs will be discussed. Common curtain wall systems include:

1. Sticks System—tectonically built piece by piece,
2. Units System—larger systems installed as sections,
3. Unit-Mullions System—hybrid between sticks and units,
4. Panel System (more typical of precast concrete), and
5. Column-cover-spandrel System—hybrid of spandrel.

First, we must establish the baseline for all systems to be compared. The typical window-wall building with continuous spandrel or extension of the floor/roof plates shall be used in this example. Window-wall buildings are composed of a structural spandrel and window framing units that fit within the spandrel.

[49] If future core materials can be developed from noncombustible materials, their use and deployment may broaden in multistory construction.

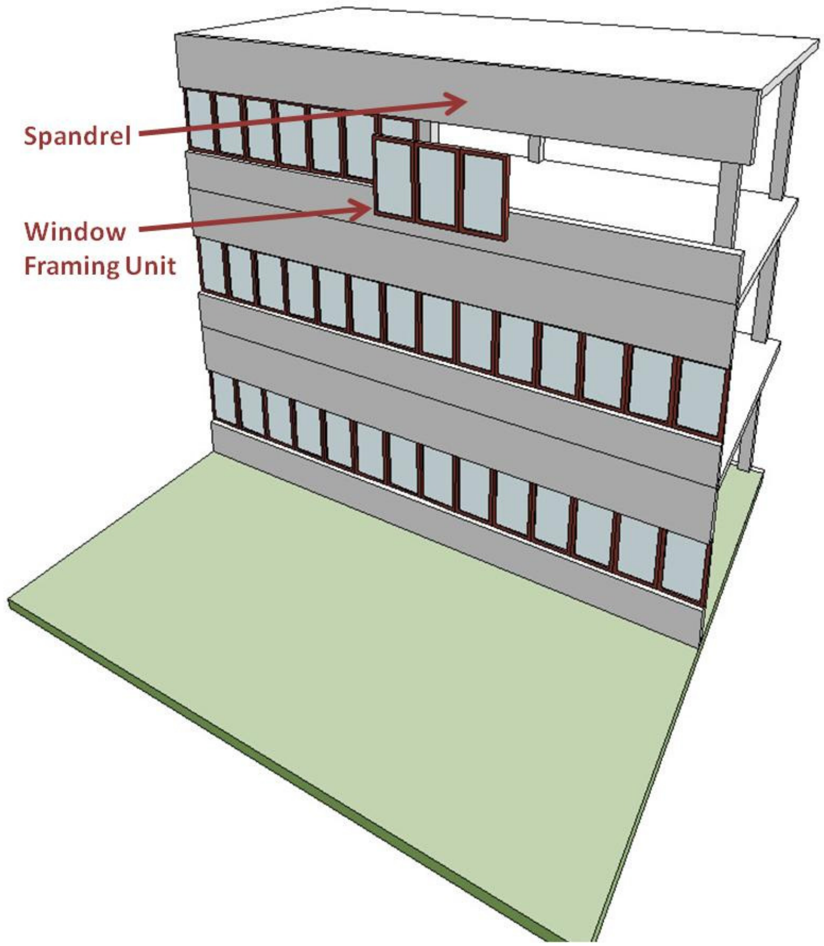


Figure 41 – Typical Building with Continuous Spandrel and Window Framing Units

3.4.1 – Stick System

The Stick System is comprised of many individual parts installed on-site to form a unified system. Therefore, it is tectonically built piece by piece and does not take advantage of the benefits of pre-manufacturing. The advantages are in the shipping of many small parts, providing many opportunities for adjustment, and requiring that all joints are interdependent. The main disadvantage is the system requires more field work than factory work.

The main components of Stick Systems are:

a. Anchors,
b. Mullions (vertical) running across floors,
c. Horizontal rails at header and sill locations,
d. Infill panels,
e. Horizontal rails at sill and header, and
f. Infill window units.

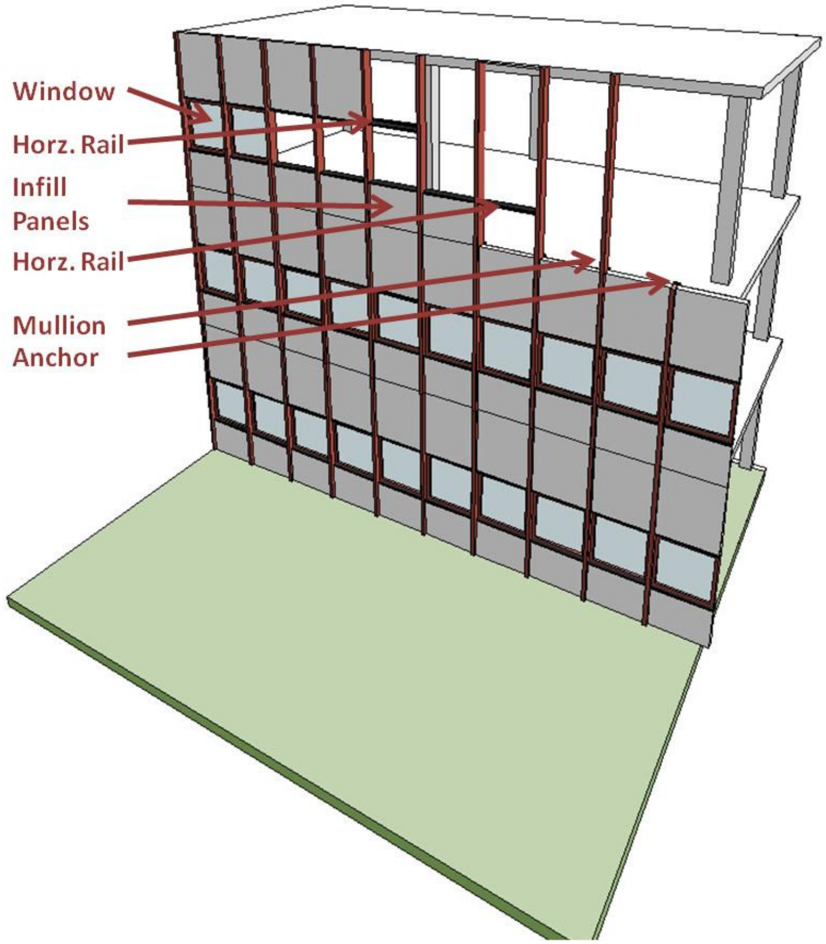


Figure 42 – Stick System

3.4.2 – Unit System

The Unit System is comprised of larger, factory-crafted/manufactured systems installed as sections. The Unit System leverages manufacturing and the factory environment to control system quality and apply that system on the building frame. The main advantages are the system's factory-crafted main components, minimized field work, in-factory rather than in-field testing, and independent joints. The primary disadvantages are the increased shipping costs (due to the size of the units), the limited adjustment of unit dimensions on-site, and the fact that the joints are independent and may require more attention to properly weatherize.

The main components of the Unit System are:

a. Anchors and
b. Independent Unit Systems.

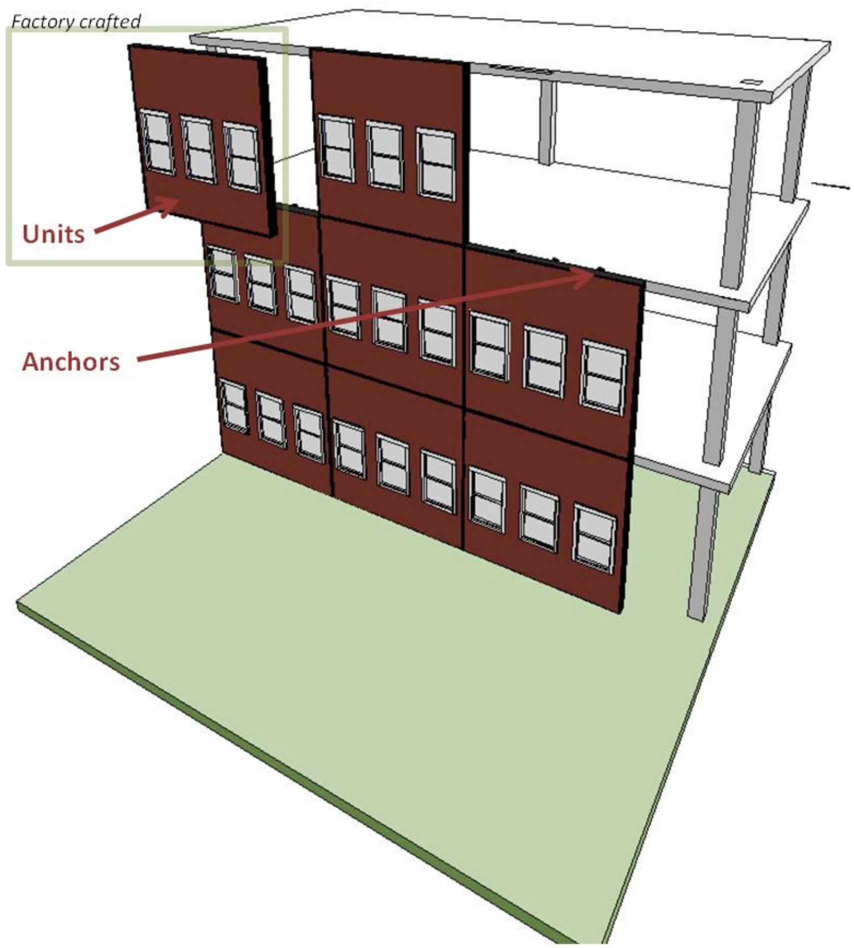


Figure 43 - Unit System

3.4.3 – Unit-Mullions System

Unit-Mullion Systems are hybrids between the sticks system and the units systems, where mullions help tie the individual units to the building frame. The advantage of the system is the mullions adapt the unit system to the building and are a means of collecting and draining water to the lower floors, weatherproofing, and expanding the system to the building's frame expansion. The main advantages of the system are the factory-crafted main components, which require less field work and are factory tested, and that the joints need to be independent to allow for movement. The main disadvantages are the potential increased shipping costs (due to the size of the units), the limited adjustment on site, and that the joints are independent and may require more attention to properly weatherize.

The main components of the Unit-mullions System are:

a. Anchors,
b. Mullion (vertical) running across floors,
c. Assembled sections as units, and
d. Interior rails at the sill and header to control water management.

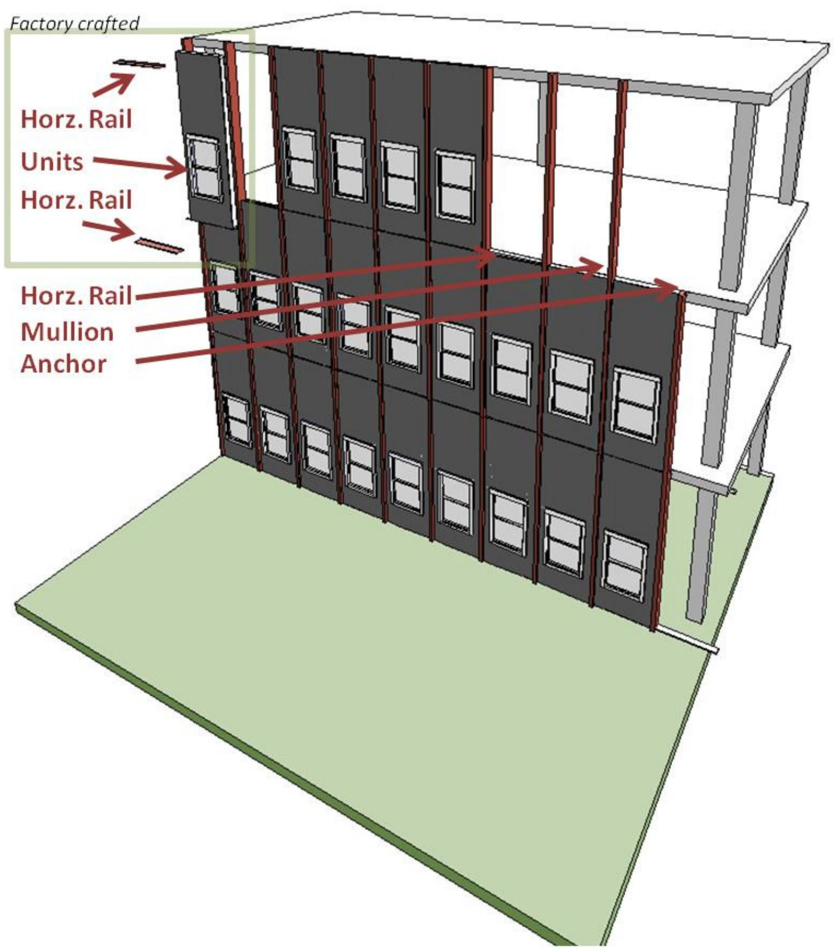


Figure 44 - Unit Mullion System

3.4.4 – Panel System

Panel Systems are more typical as precast concrete systems. Their main advantages are that the system is the system's factory-crafted main component, requiring less field work, and is factory-tested, requiring few internal joints, yet they are required to be independent to compensate for movement. Additionally, as they are traditionally made of precast concrete, they commonly are architectural in character with ornamentation and other details cast in place. The primary disadvantages are increased shipping costs (due to size and potentially weight), limited on-site adjustment, and that the joints are independent. The main emphasis of the system is on the joints—primarily its perimeter joints.

The main components of the Panel System are:

a. Anchors and
b. Homogeneous independent panel units.

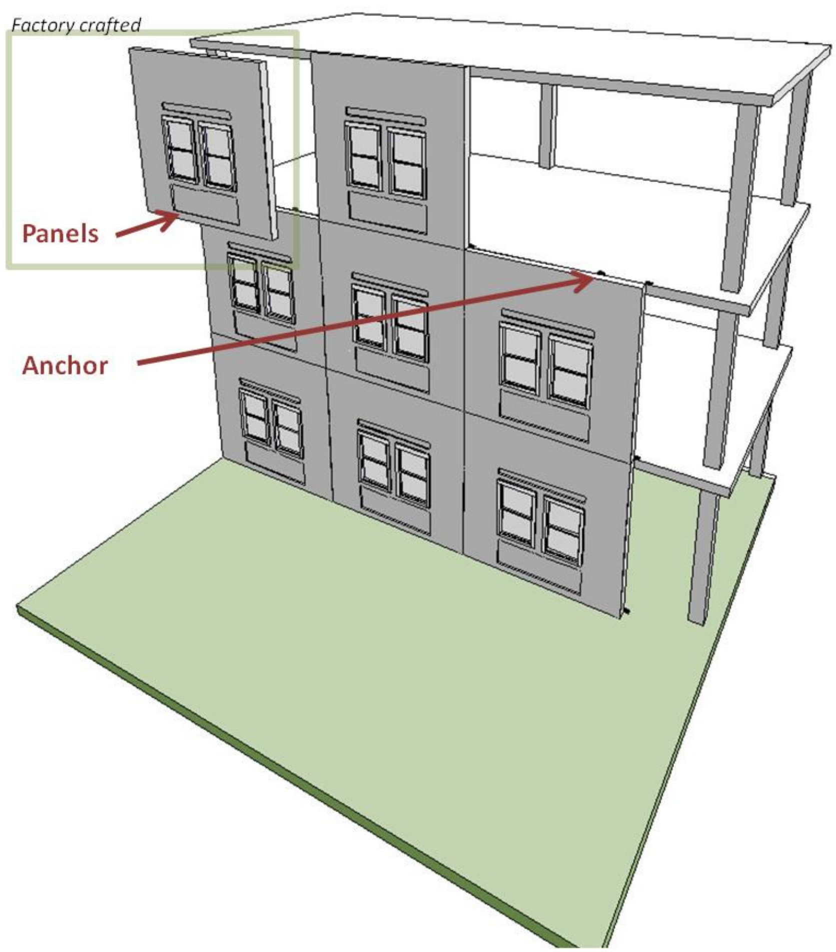


Figure 45 - Panel System

3.4.5 – Column-cover-spandrel System

The Column-cover-spandrel System is a less common system. It is comprised of an engineered assembly that houses all of the system's connections to the frame, which are then covered. The main advantages of the system are that it architecturally expresses the structural frame, is comprised of large sections that are factory-crafted, requiring less field work, and can be factory tested. Additionally, the joints need to be independent. The main disadvantages are similar to that of the panel system, which may require increase shipping (due to size) and allows only limited adjustment on-site.

The main components of the Column-cover-spandrel System are:

a. Column cover section,
b. Spandrel panel, and
c. Infill (typically glazing).

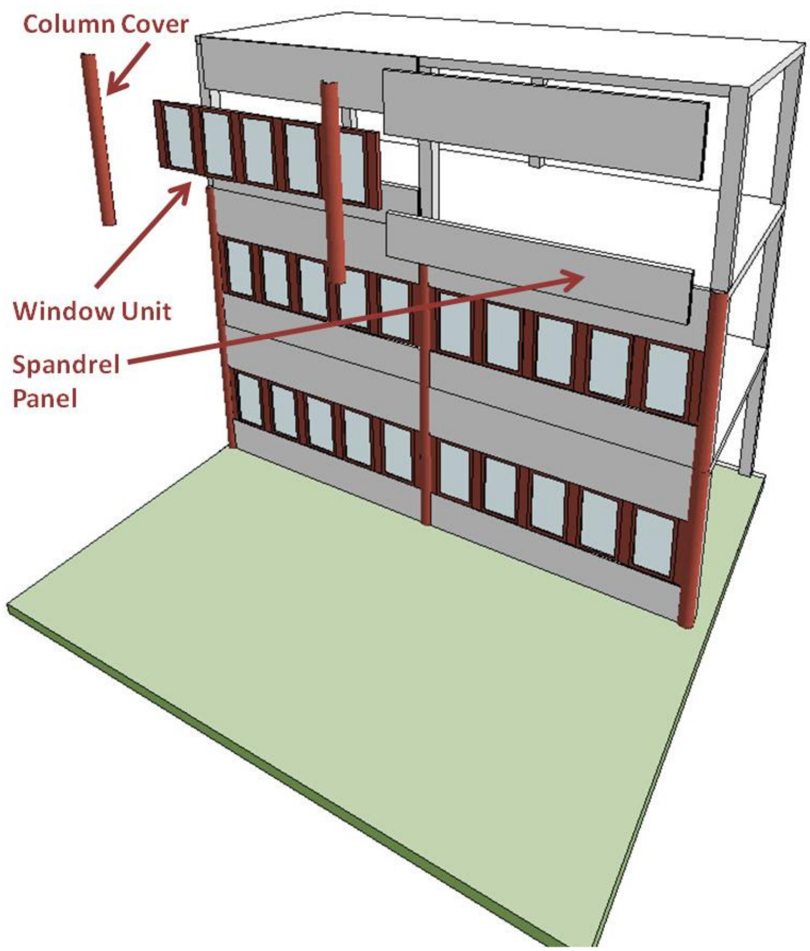


Figure 46 - Column-cover-spandrel System

3.5 – Evaluating Curtain Wall Possibilities for CSIPs in Multistory Design

After reviewing the performance of CSIPs and the constructability of CSIP assemblies, the following list describes the application of CSIPs in each of the five curtain wall systems:

1. Sticks System: limited application and use of CSIPs as infill panel, as the infill panel areas are small and all the panel advantages are fully leveraged.
2. Units System: applicable to CSIPs, as the larger system is installed as sections. The system is a candidate based on constructability, cost, and performance of the CSIPs being leveraged.
3. Unit-Mullions System: similar to the Unit System, its hybrid nature between sticks and units make the system a candidate based on constructability, cost, and performance of the CSIPs being leveraged.
4. Panel System, more typical of monolithic precast concrete, is discouraged due to aforementioned limitations and the requirement that the CSIPs have a substructure or panel frame to tie the 4’x8’ to 4’x12’ panels together. Unit system is similar to panel system but more applicable to CSIP’s constructability.
5. Column-cover-spandrel System, as a hybrid of a typical spandrel condition, this system is discouraged due to aforementioned limitations and the fact that the unit system is more applicable.

3.6 – Proposed Wall Types and Application of CSIPs

Two systems are proposed herein: the Unit System and the Unit Mullion System. These systems were chosen because they take advantage of CSIP’s properties and manufacturing methods. Additionally, they can easily accommodate multiple panels built up into a unit, and the per panel limitations of the nominal 4’x8’ to 4’x12’ module common in the fiber-cement facing industry. Each of these systems relies on a heavy use of factory-crafted parts, manufacturers testing the systems before installing them in a building, and finished systems that require minimal additional layers for finished construction.

Each of these systems will be dissected below to understand the components and the issues relating to applying them onto buildings.

3.6.1 – Unit System

A CSIP unit system is comprised of units manufactured from multiple individual SIPs with a substructure or frame that bounds the units. The following parts are needed for a complete system:

1. Intermediate Frame,
2. Panel System,
3. Window Units, and
4. Exterior Trim.

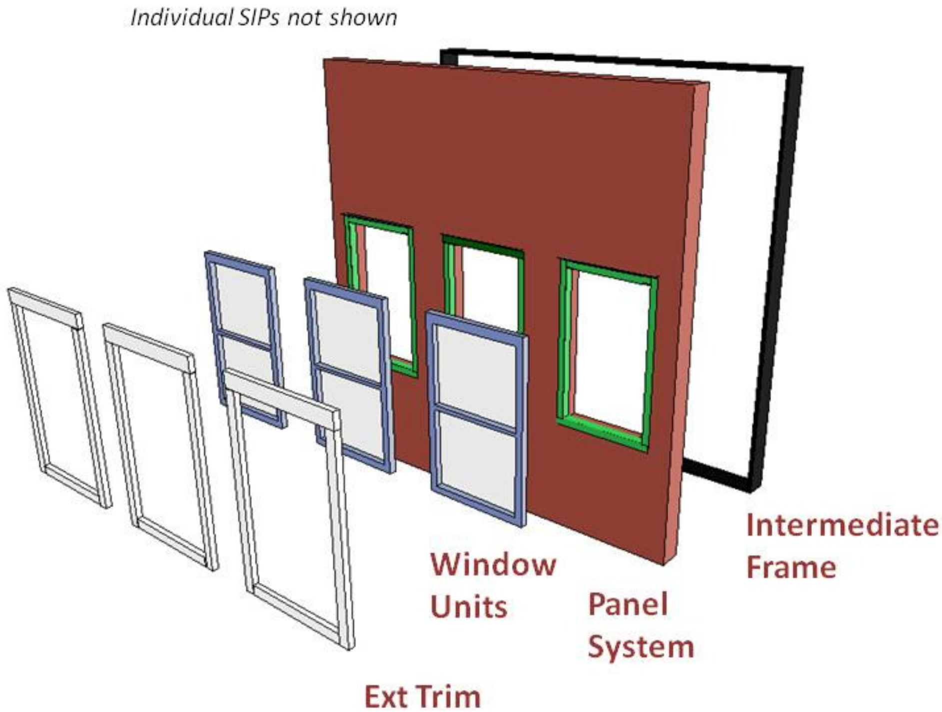


Figure 47 - Components of Unit System

The Design Considerations for Unit Systems include:

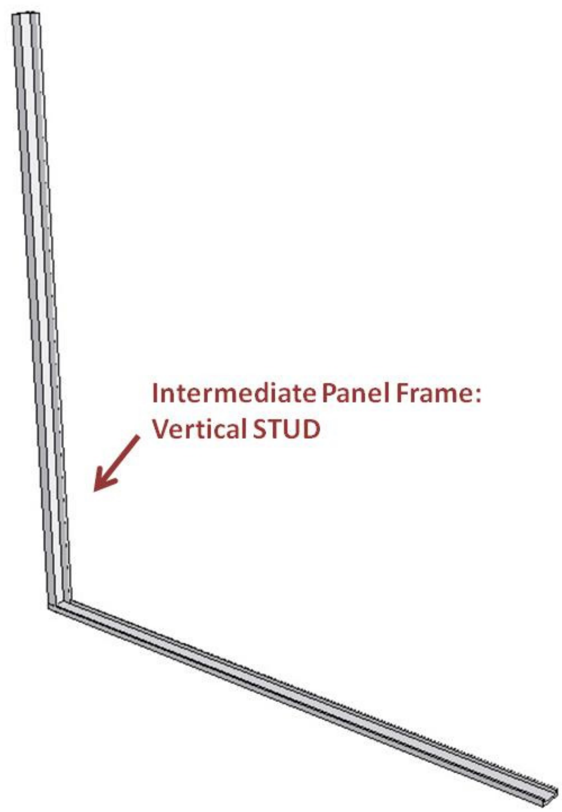
- Anchor to frame details, which allow movement,
- Intermediate frame specifications and water management details between frame and unit,
- Panel System type (the selection of the CSIP system and supplier), the connection system between the panel and the frame AND panel to panel (spline type), the design/performance values of the panels and the assembled unit, and finishing specifications (exterior for the weather barrier and interior for the thermal barrier);
- Window unit type (and U_o Values), installation and flashing details; and
- Exterior trim type, design values, installation details and specifications.

Constructability of CSIP Unit System Curtain Wall Unit

Step 1: Substructure base

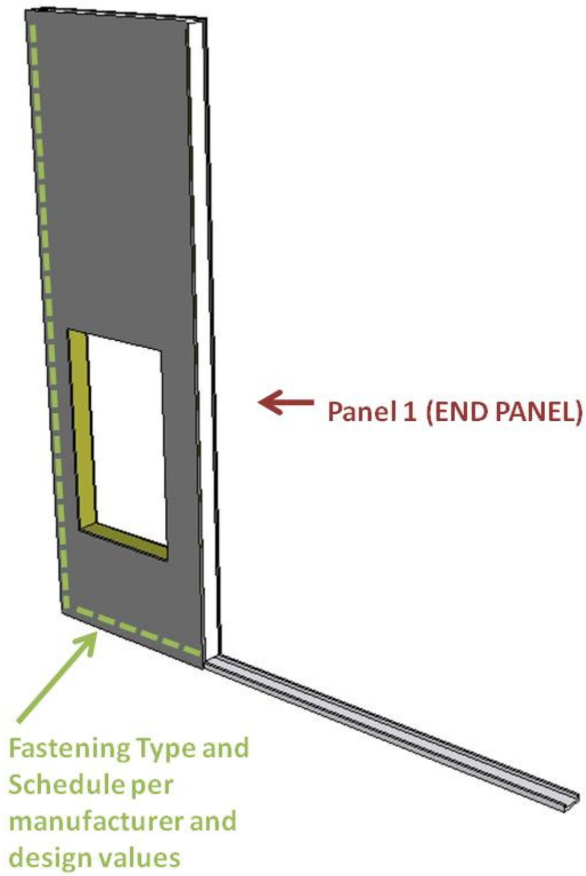
Design Considerations include: track span, track material, track thickness, connection of track to building frame.

Step 2: Unit frame



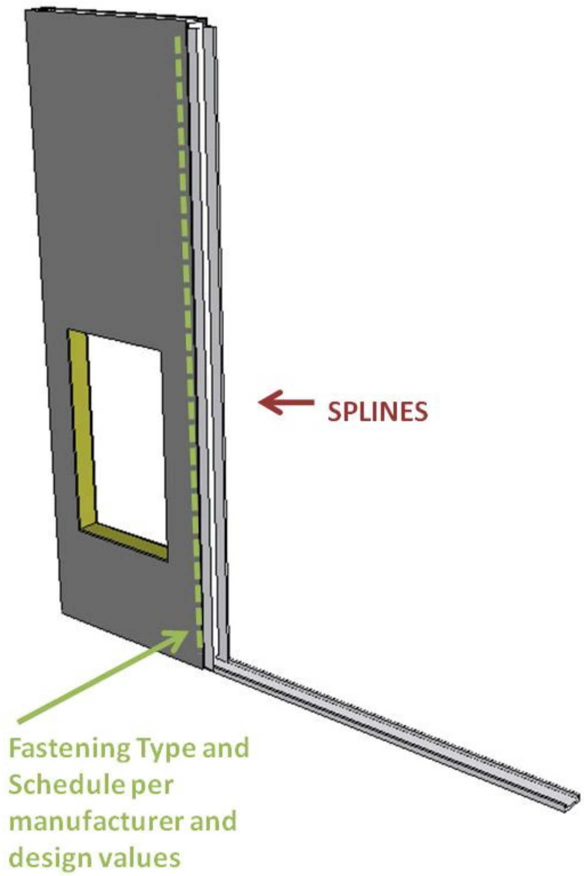
Design Considerations include: Stud Span, Stud Material, and Stud Thickness.

Step 3: Installation of First CSIP



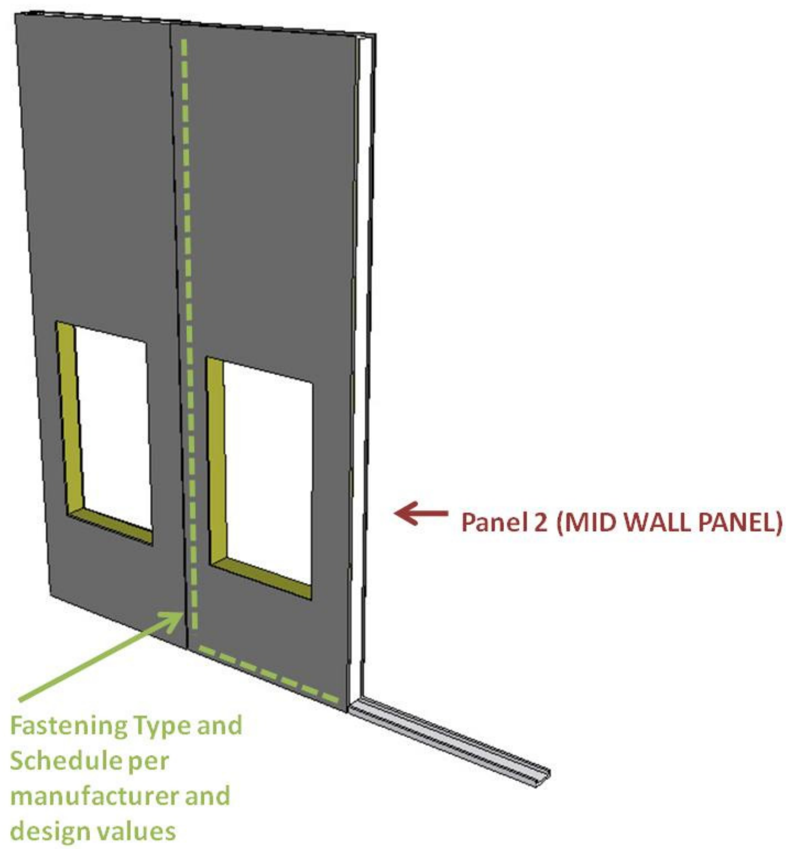
Design Considerations include: Panel Span, Panel Material, Measured Panel Performance, Panel conditions of use, Panel Thickness, Panel Design Values.

Step 4: Installation of Spline



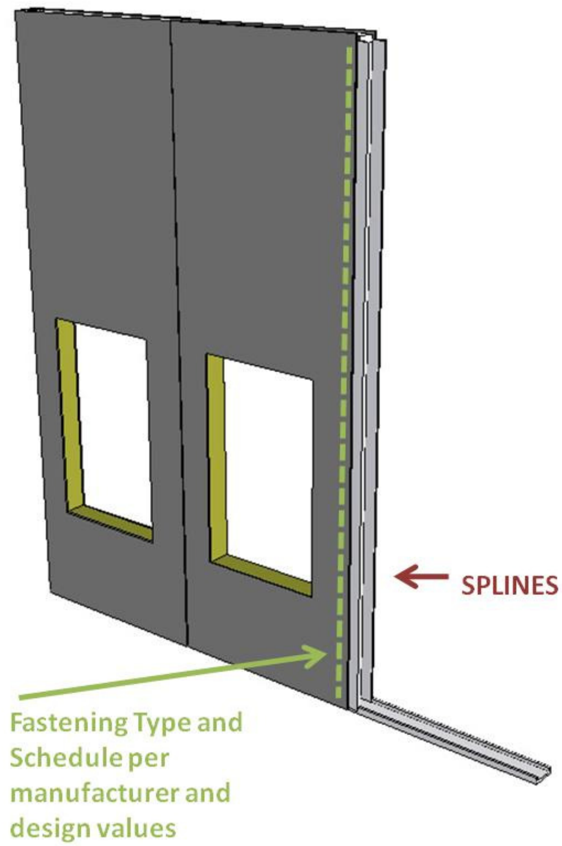
Design Considerations include: Panel Span, Panel Material, Measured Panel Performance, Panel conditions of use, Panel Thickness, Panel Design Values, Tested Spline materials, Tested Spline connections, Tested Spline limitations.

Step 5: Second CSIP Installation



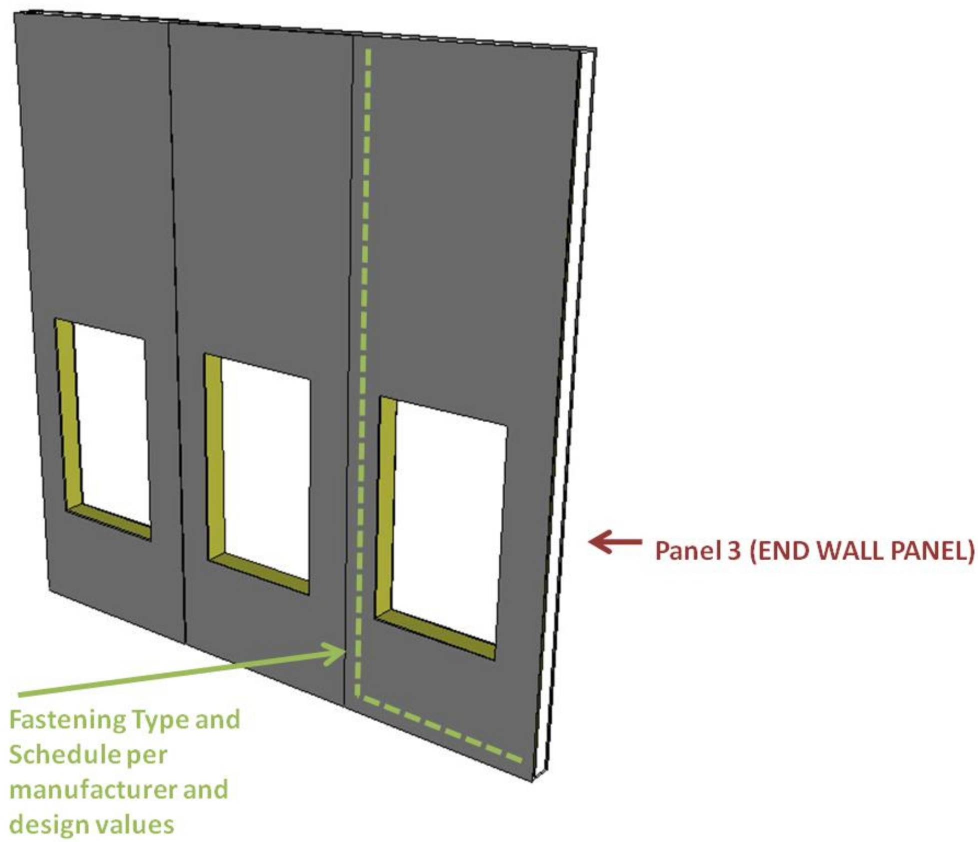
Design Considerations include: Panel Span, Panel Material, Measured Panel Performance, Panel conditions of use, Panel Thickness, Panel Design Values.

Step 6: Installation of Second Spline



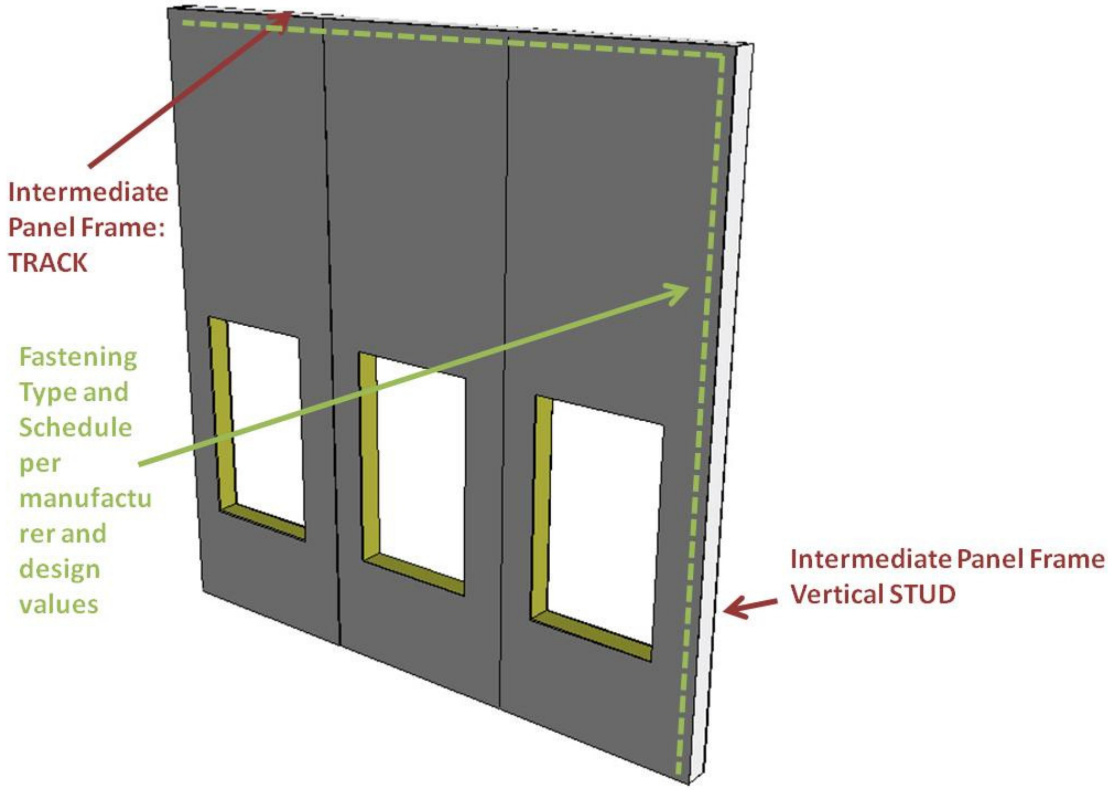
Design Considerations include: Panel Span, Panel Material, Measured Panel Performance, Panel conditions of use, Panel Thickness, Panel Design Values, Tested Spline materials, Tested Spline connections, Tested Spline limitations.

Step 7: Installation of Third Panel



Design Considerations include: Panel Span, Panel Material, Measured Panel Performance, Panel conditions of use, Panel Thickness, Panel Design Values.

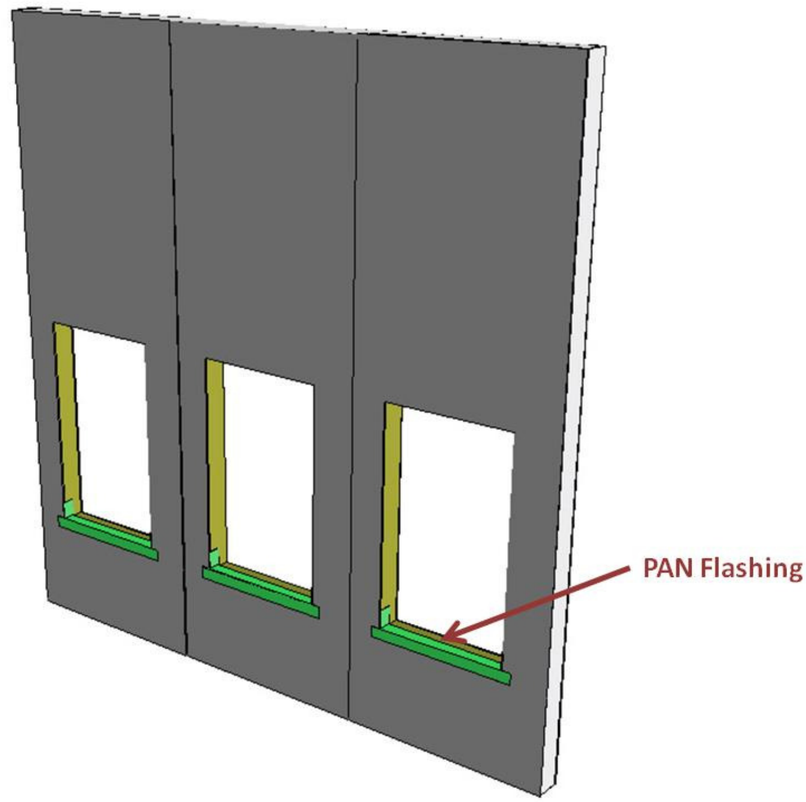
Step 8: Finalization of Substructure



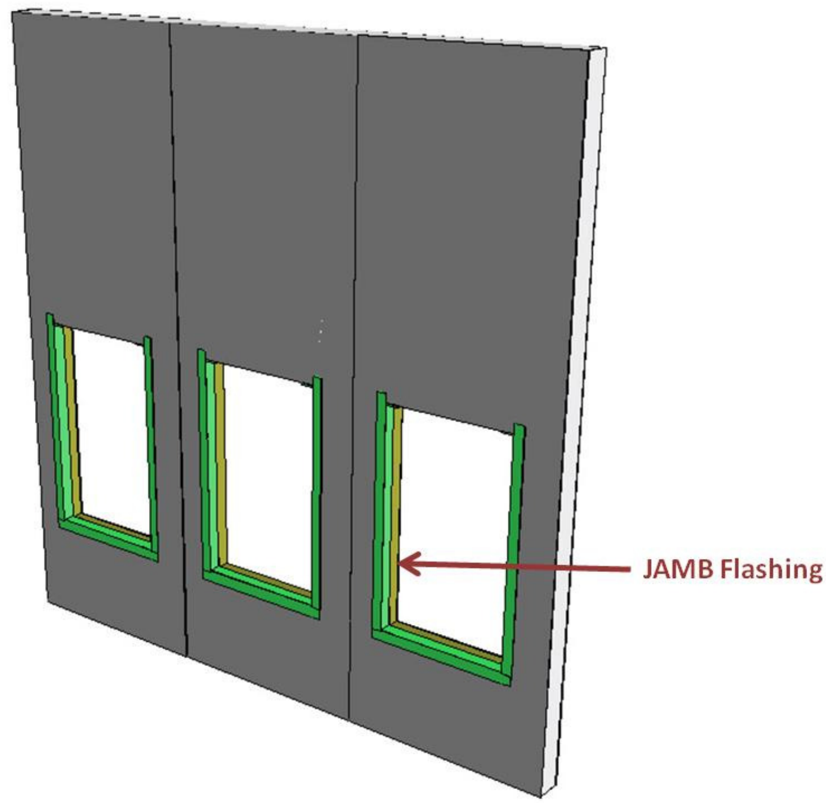
- *Typically within this step the joints are finished and the surface is prepped primed or finished with a intermediate course.*

Design Considerations include: Stud Span, Stud Material, Stud Thickness, Track Span, Track Material, Track Thickness, Connection of Track to Building Frame.

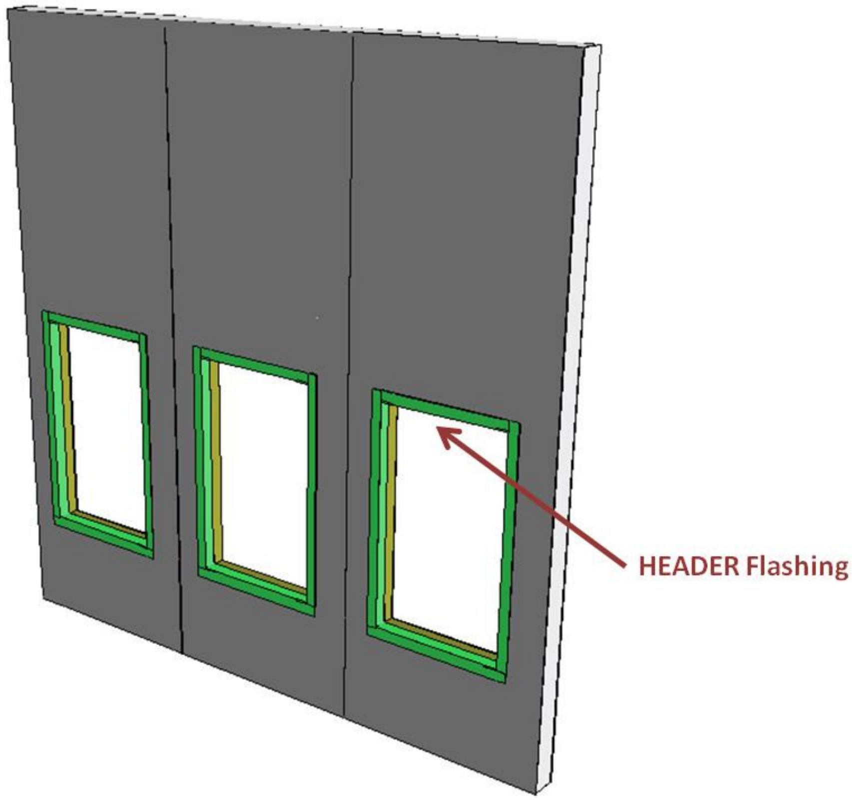
Step 9: Weather Barrier (CMU block fill step not illustrated in this diagram but must be completed by the manufacturers).



Design Considerations include: Pan flashing material, Installation Specifications.

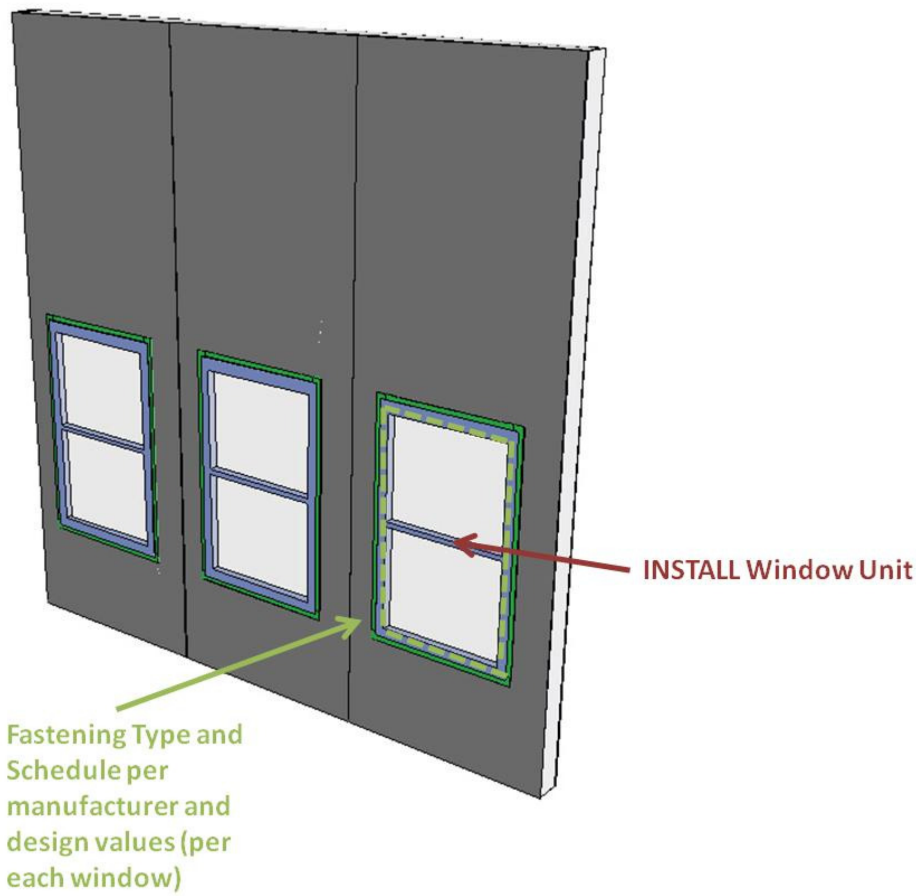


Design Considerations include: Jamb flashing material, Installation Specifications.



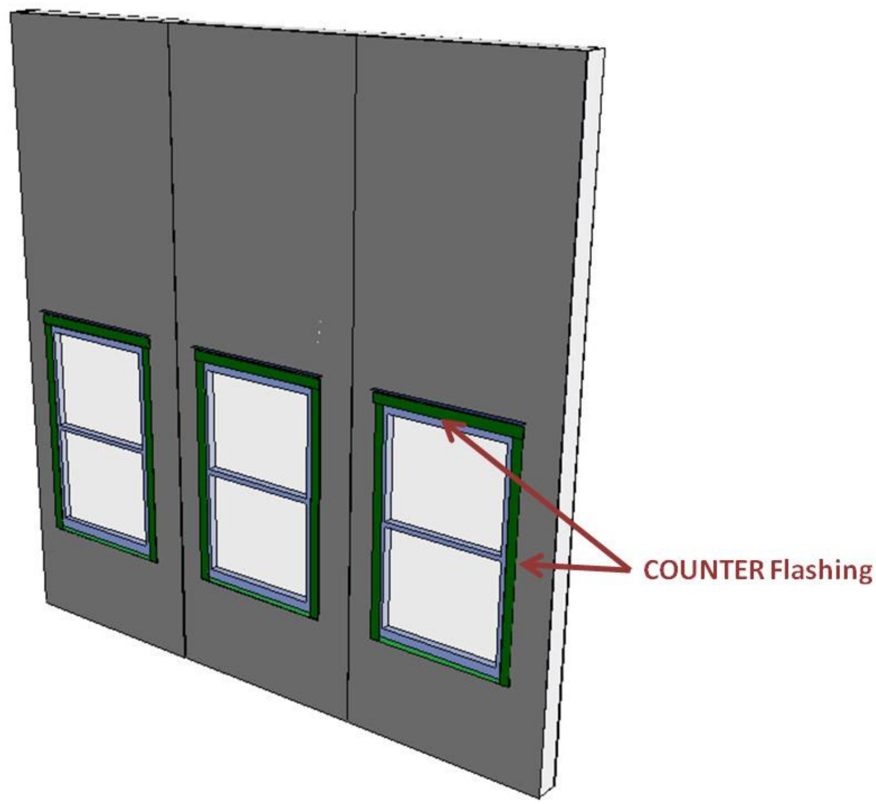
Design Considerations include: Header flashing material, Installation Specifications.

Step 10: Window installation

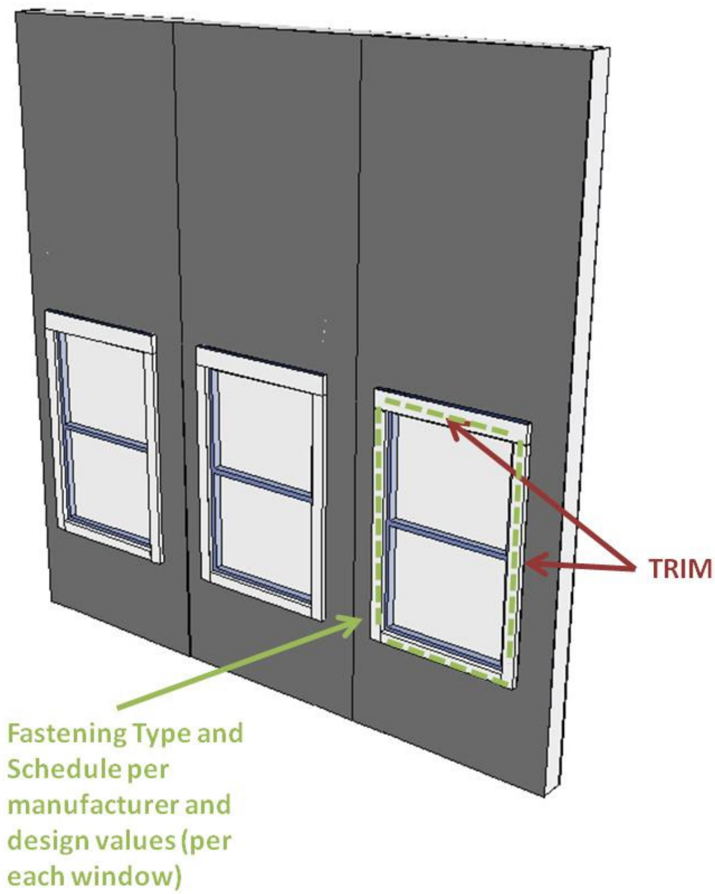


Design Considerations include: Window type, Installation Specifications.

Step 11: Finishing Details



Design Considerations include: Counter-flashing material, Installation Specifications.



Design Considerations include: Trim material, Installation Specifications.

3.6.2 – Unit-Mullion System

Similar to the Unit System, a CSIP Unit Mullion System is comprised of units manufactured from multiple individual SIPs with a substructure or frame that bounds the units. The difference in the Unit-Mullion System is that the mullions act as an intermediary with the anchoring system, thereby creating a larger area to form a secondary seal. Additionally, a sill for water management can be installed into this mullion system for added water management. The following parts are needed for a complete system:

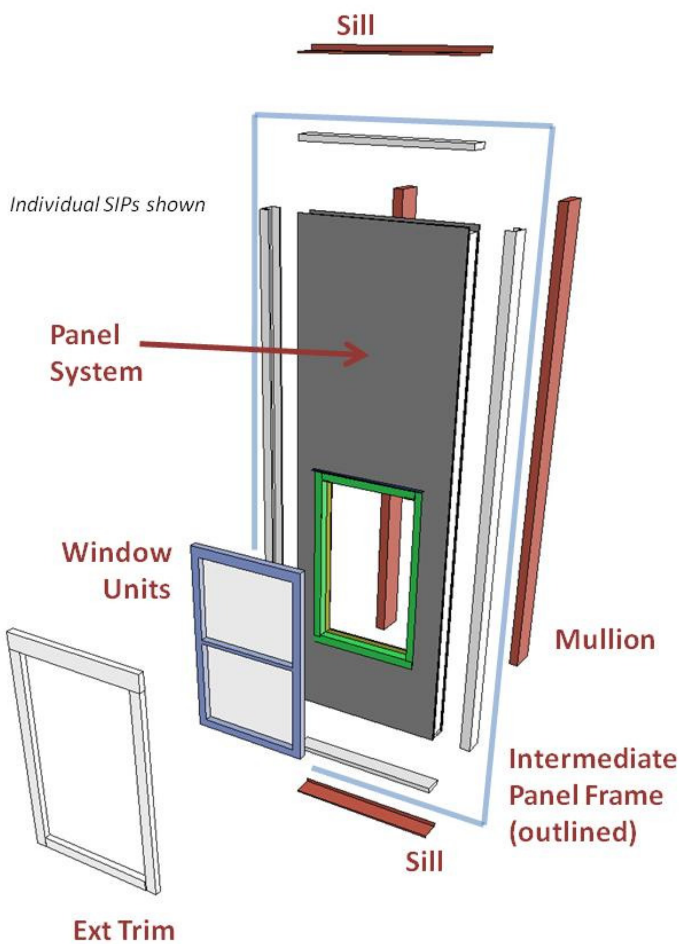


Figure 48 - Parts of the Unit Mullion System

Please refer to the Unit System for the individual steps and design concerns needed to construct the assembly and the weather and thermal barriers.

3.7 – Design Considerations

There are many design considerations for applying CSIPs to multistory construction, stemming from requirements of the overall building envelope system as well as the need for panel optimization. The following design concerns and issues must be addressed for CSIP application:

- Selection of Panel: given quality assurance and quality control of panel system manufacturing, structural data, and test reports, determine code compliance of panels system/vendor; examine technical support and track record of vendors;
- Structural Issues:
  - General: primary concern governing all decisions is the life safety of building occupants; must address movement, lateral forces, and negative pressures around building edges;
  - Structural Analysis: analysis of panel properties; analysis of panels as a system with substructure; analysis of system to the building frame; consult manufacturer for connections; limitations in regard to seismic; anchoring details and anchor to frame type dependent on building frame design;
  - Curtain Wall System: detailing the intermediate frame, panel system type, penetration control for the window unit type, exterior trim type, and construction of the totality of the unit system assembly; considerations for water, air, and vapor barriers;
  - Construction-related: tolerances should be designed to include construction and shipment; quality assurance and quality control of the vendors;
- Movement:
  - Movement in wall components, between components, and relative between wall and frame; temperature deformation and wind driven deformations; manufacturers to determine expansion contraction rates and non-structural deformations.
  - Detailing joints: the larger the joint or longer the member, the more movement in the system; horizontal and vertical joints both must be considered; considerations for water, air and vapor barriers; constructability concerns.
- Weatherization & Moisture:
  - Moisture control to withstanding the elements: moisture and condensation control; rain penetration control; air, vapor, moisture barrier concerns.
  - Thermal control to guard against temperature-driven heat transfer and infiltration; optimization of connections and boundary conditions: baseline panel (CSIP thickness governs), substructure joints (CSIP to unit boundaries and unit to unit connections—thermal shorts govern), spline joints (CSIP to CSIP connections), and penetration joints (CSIP to penetrating unit connections—thermal shorts govern);
- Fire Safety: Combustibility and limitations governed by the code; fire rating of the system; validating the candidate system to the code; core material govern;
- Constructability & Testing: not all designs require testing; small buildings rarely specify testing; larger buildings projects testing is required; test to accepted industry standards.

4 – Design Procedure Document: Application of CSIPs to Multistory Construction

This document applies to CSIPs, which shall be defined by a fiber-cement facings laminated to a foam core of EPS or Polyurethane (for more information about SIPs and CSIPs, refer to section 1.3). This document does not apply to the design of reinforcement materials that may be incorporated in some CSIPs or occurring at CSIP joints. All other materials, such as reinforcement materials, should be designed in accordance with the appropriate codes and standards.

This document details the procedure to use for the final design of, and for obtaining building officials' approval of, construction of multistory buildings higher than three stories utilizing CSIPs. It is intended that this document be used in conjunction with competent engineering design principles, accurate fabrication and vendor technical supports, and adequate supervision and review of construction. The authors assume no responsibility for errors and omissions in this document, nor for engineering design, plans, or construction based on it. It is always the final responsibility of the designer to relate design assumptions and reference design values to make design adjustments appropriate to the end use. The authors make no warranty, either expressed or implied, regarding CSIPs and their use as covered in this report.

Please note:

- All details should be developed by the manufacturer, designer, and consultants on a case-by-case basis. However, common details are shown below and throughout this document.
- The designer must specify the connections of the systems to the building. Specialized knowledge of the system is required to provide correct design detailing to the building. Most suppliers provide technical support to address these needs. Additional information may be obtained from consultants or manufacturers.
- Not all designs require testing. For small buildings, it is rare to specify testing as long as performance data for the application, use, and details is available from the manufacturer along with panel certifications (refer to Section 4.2.1 for more information). For larger buildings and projects, testing is required to ensure all details and assumptions meet or exceed the performance requirements. Additionally, for large buildings, it is recommended that the systems be certified for the specific use following the details supplied. Testing of individual panels is referenced in Section 2.0 and testing of unit wall systems is discussed in Section 4.7.

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4.1 – Introduction: Designing for Sustainability and Structural Performance

CSIPs are optimally used in applications in which sustainability, maintaining durability of the installation, high insulation, and thermal breaks are key project needs, as the unbroken layer of insulation of CSIP's core reduces air infiltration while increasing the whole wall thermal barrier (as discussed in Section 3.2). However, CSIPs also provide their own structural integrity when combined into a substructure or frame.

The primary goal of this section is to provide a basis for the design and adaptation of CSIPs to multistory construction by referencing engineers and professionals to the previous chapters for more in-depth discussion and analysis.

The sustainable performance criteria must simultaneously consider the functions of energy efficiency, thermal efficiency, and building tightness (through the thermal, weather, and air barriers). One of the principal reasons for selection of CSIPs is their insulation qualities. Additionally, the system supports lower glazing to wall area ratios, which dominated buildings before glass curtain wall construction was commercialized. In this regard, there is a greater unbroken area of traditional insulation than glazing. Also, because the glazing area is less, the glass and window unit can be of a higher quality and use low-e glass to minimize the penetration points for air infiltration.

The designer should understand the basic advantages of CSIPs, explained in detail in Section 1's discussion of their sustainability performance values. Some of the major characteristics of CSIPs to be leveraged are:

- <u>Thermal performance:</u> Insulation is crucial to the structural make-up of a SIP, and it follows that the end product carries high quality thermal performance. Panel connections are designed to eliminate thermal bridging, a common problem in stick-frame construction. What results is a building envelope with a higher total wall insulation value. The EPA has also recognized the exceptionally tight construction of SIPs through its ENERGY STAR rating system. Stick-built construction requires a pressurized blower door test to check the air tightness of a home. However, in December 2006, the EPA replaced the blower door test and energy modeling calculations normally required to meet ENERGY STAR qualifications with a visual inspection form for homes built with SIP walls and a SIP roof.

- <u>Construction time:</u> It is difficult to quantify decreases in construction time, as this differs significantly between projects. However, because SIPs constitute an entire wall assembly and are shipped to a job site ready to be placed on a foundation, construction is simple and quick. If a project uses CSIPs, which don't require finishing on interior or exterior surfaces, several more steps are removed from the construction process, further decreasing construction time. This results in reduced labor costs and faster project timelines.

- <u>Increased comfort:</u> Heating and cooling is more evenly distributed in a SIP home. SIP walls have a more consistent temperature, free of the spikes found with frame wall construction. This is a difficult quality to measure, but it has a significant impact on occupant comfort.

- Decreased job site waste: By using prefabricated panels in construction, significant waste is avoided on the construction site.

However, as a design strategy, to fully leverage the sustainable performance of the assembly, all connections and details must be considered to reduce air infiltration, reduce thermal bridging, and optimize production and structural capacities. These issues will be addressed in this section.

This section is broken down into pre-design, design, and testing activities.

4.2 – Pre-Design Activities

This section deals with the qualitative issues relating to CSIP designs, including the process of selecting a candidate system and planning issues.

4.2.1 – Selection of a Candidate CSIP for Application

The first issue designers must consider is selecting a candidate CSIP for application. Quite simply, the engineer must select a CSIP with a demonstrated track record in residential, commercial, and multistory construction. While the SIP industry is flourishing, few manufacturers produce CSIPs, but it is this document's goal to highlight their value and unique issues to educate both existing and future manufacturers, architects, engineers, and consumers.

Panel system manufacturers must be evaluated to ensure their products comply with the model codes, have an ongoing quality assurance and quality control program, and have tested design values for the system's performance. The first role of the design professional is to evaluate the available panels and choose a candidate by using the decision tree to validate candidate panel systems. This process is discussed and detailed in Section 2.3.1. There are three methods to validate a CSIP system as a candidate system:

A. Using code-recognized systems (currently, CSIPs are not recognized specifically in the model codes),
B. Using a certified, listed, or evaluated panel system (that has certification from a recognized product certification agency; for an in-depth discussion, refer to Appendix C), or
C. Using an uncertified system (which is discouraged; if manufacturers are selling uncertified systems, it is recommended that they work with a recognized product certification agency to certify their products).

Method 1: Using code-recognized systems:

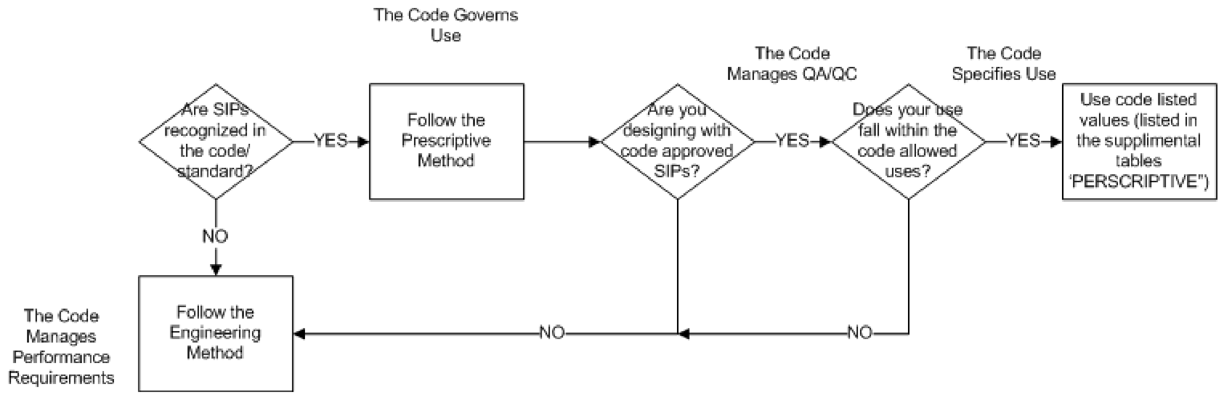

Figure 49 - Code Recognition Decision Chart

- The designer must consider whether SIPs are recognized by the code. If the code specifically and discretely references SIPs, the design professional can simply follow the prescriptive methods outlined in the code for use and application.

  Currently only one code recognizes SIPs—the IRC in a supplement[50]—and it is being carefully revised by SIPA. If a code recognizes SIPs, then a designer must simply verify the product is code approved or meets the code definition to complete Step 1a.

  If the code does not address SIPs, use Method 2.

- *STEP 1a: Is the product being reviewed a code approved SIP?* This step simply ensures the designer the product being used falls within the code and is not another product that may be designed for another use. Currently, SIPA is in the process of helping the industry standardize a consensus standard and definition for a SIP[51] and develop expectations in terms of quality and manufacturing. All of these activities are done through a transparent standards development process open to the public for participation and public comment.

- *STEP 1b: How does the code limit SIPs?* Understanding the system's limitations is as important as understanding its performance.

- *STEP 1c: Use the listed values for the engineering analysis and design.* These values are listed in the supplemental tables, such as the ICC addendum.[52] The current status of SIPA's activities is to develop ANSI standards for the manufacturer to define SIPs and work within the ICC to get SIPs specifically and discretely into the code. For example, SIPA has focused on wall panel in

[50] See Appendix A.
[51] See Appendix E.
[52] Appendix A.

residential construction to start this development within the IRC, so the limitations currently apply to walls.

If the code specifically and discretely addresses SIPs, the designer has less to worry about in terms of managing the product he or she is trying to deploy because the code defines the QA/QC standards for the manufacturer to follow, the use of the system in buildings, and the design values to be used. These benchmarks are ones the industry is moving toward, but unfortunately, they will take time and do not yet apply to multistory construction. Therefore, the designer's liability is narrowed to simply correctly applying the code to the design and specifying a code-recognized system.

Method 2: Using a certified, listed, or evaluated panel system:

If a code doesn't govern the system use, the designer must follow the engineering methods, as the code solely manages the requirements the panels must meet. Now the designer needs to determine whether the panels are properly tested, manufactured, and have specified design values to be used in the application of the system to the code requirements. As you can see here, the liability is widening.

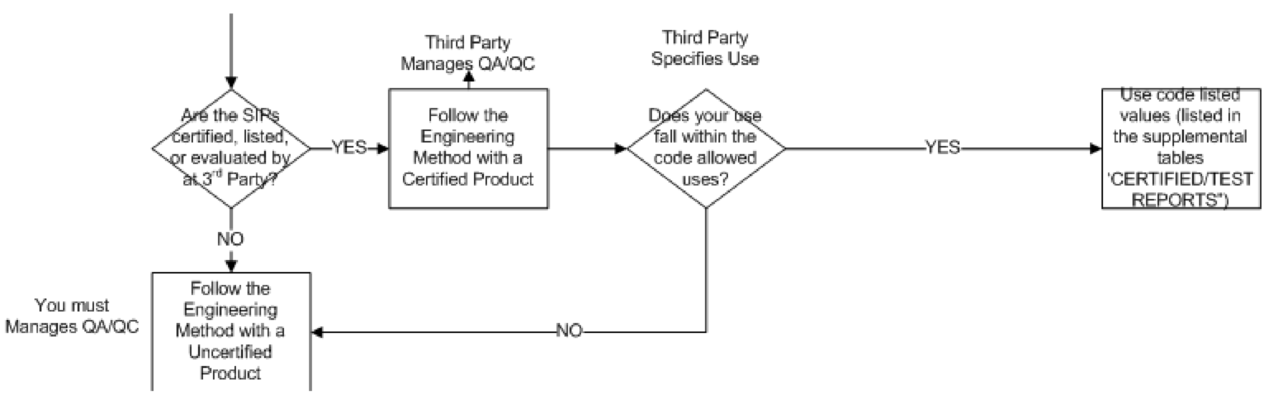

Figure 50 - Decision Chart for Certified, Listed, or Evaluated System

In Step 2a, the designer must consider whether the SIPs are listed by a certification or evaluation agency. Product certification and product evaluation are very similar things, and they provide a similar argument for code compliance. However, there are subtle (yet important) differences.

Product evaluation simply verifies specified testing has been done to show a building product, component, method, or material performs at a level compliant with applicable codes. It reviews test reports to make sure the correct testing was performed, and then issues a third-party statement to that fact. While product evaluation exists as a snapshot of a product at one moment in time, product certification provides an ongoing view into compliance.

Product certification agencies identify and run the required testing, evaluate the results, produce a certification report, and monitor quality control of production. These differences are largely in terms of the chain of custody between sampling, testing, and ongoing quality assurance. A more in-depth description of these differences is included in this report as Appendix C.

If the panel company doesn't have a certification or evaluation report, the designer must follow the engineering method with an uncertified product as Method 3. If the product to be used is not certified or evaluated, the engineer should consider using a different system, as there is more management he or she must do with the actual product and manufacturer. Although this work is not impossible, it is time-consuming and it may expose the engineer to liabilities for which he or she is unprepared or unknowledgeable.

However, it is very common for panel manufacturers to have listings by a certification or evaluation agency. This issue has been specifically addressed over time, and most modern companies maintain a current listing. In fact, this certification requirement is a mandatory requirement for SIPA members.

- *STEP 2a: Is the use within the scope of the panel certification?* If the desired use is not listed or the intended design falls outside the scope of use, the designer will have to proceed to Method 3. If the application falls within the certification's scope of use, the listed performance and design values in this certification or evaluation can be relied upon.

Method 3: Using an uncertified system

If the code doesn't recognize SIPs and the product to be used doesn't have a certification or evaluation or the intended use falls outside the scope of the certification or listing, the engineer can evaluate the panel and the manufacturer and determine the scope of use with the code and code-referenced documents. This process will require the designer to evaluate the SIP company and SIP system.

This is the most laborious method, as it puts the requirement of quality assurance and quality control in the hands of the design professional. Before evaluations and certifications, this was the only option for application, and many small companies still put these burdens on the design professionals. Additionally, this approach puts the burden on the design professional to understand everything they must consider, review, and feel comfortable assuming liability for in their application of the system to the use. This leads to engineers being conservative (rightfully so) and panel use being uncompetitive with traditional systems.

WARNING: whereas CSIPs can be applied to buildings following Method 3, this type of CSIP deployment is discouraged because it places more burden on the engineer and less on the manufacturer. Please review Appendix C before considering this method.

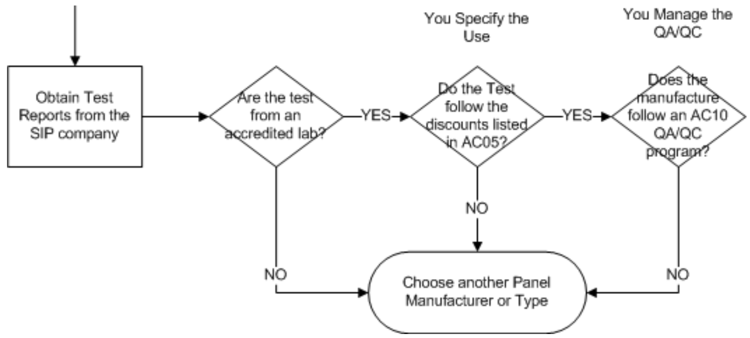

Figure 51 - Decision Chart for an Uncertified System

- *In Step 3a, the designer must consider whether the panel was tested by an accredited third party lab.* If not, the engineer should choose another system as there's no assurance an independent third party has completed the required tests.
- *In Step 3b, the designer must determine if the system complies with the industry consensus standards listing the test requirements, the safety factors, and other quality assurance/quality control needs.* This data can be obtained in the acceptance criteria for the code (AC04, AC05, AC10, etc.).[53] Ultimately, these documents will also be supplemented by the ANSI standards SIPA is helping develop. If in the engineer's review of these acceptance criteria, the test results are inadequate, the engineer should choose another system as there's no assurance the results are consistent with best practices.

  Note: The ICC defines three principal tests for sandwich panels: transverse load tests, axial load tests, and shear wall tests (discussed in Section 2.1.1). Factors of safety (F.S.) as calculated by ICC are:

  - F.S. = 2.0, ultimate load determined by bending failure for allowable live loads up to 20 psf (958 Pa) and wind loads.
  - F.S. = 2.5, ultimate load determined by bending failure for allowable snow loads.
  - F.S. = 2.5, ultimate reaction at failure for all loading conditions.
  - F.S. = 3.0, ultimate load at shear failure for all loading conditions.

  Use the process diagram below to determine whether the listed values are ultimate loads or allowable loads. This step is critical as many testing labs unfamiliar with SIP testing and SIP standards list incorrect allowable loads.

[53] ICC Acceptance Criteria

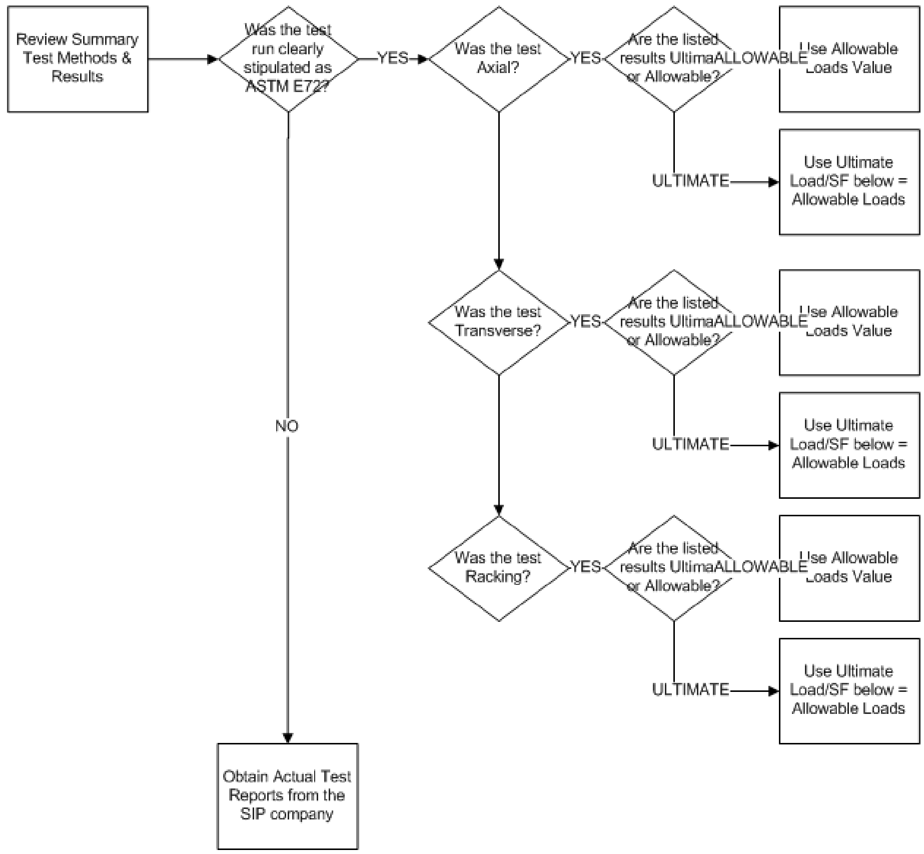

Figure 52 - Decision Chart for Reviewing Test Methods and Results

- The designer should review the in-plant QA/QC protocols to ensure the panels tested are those that are in fact still manufactured, consistently manufactured and inspected, and consistently tested to show conformance to the results being used to design the structure. The designer should ensure all the parts and pieces are certified as independent components (like the facing materials, the EPS, and most importantly the glue, which is governed by AC05).
- The designer should review the test results and resulting design values listed in AC04 to determine whether the appropriate safety factors are applied. Ultimately, these design values will be the basis for the design.

This method assumes there is a chain of custody between the results being used, the manufacturer's process, and the parts and pieces in the composite. As this is now the role of the engineer to verify and ultimately stipulate the use, the designer is entangled in the liability of manufacturing and utilizing the panels. If this cannot be determined, if the designer has reservations, or if there are any questions about the manufacturer that aren't adequately addressed, the engineer should choose another system as there's no assurance the results are consistent with best practices.

4.2.2 – Information to be Supplied to Code Officials

Code officials may or may not be educated on composite panels and SIPs/CSIPs. Therefore, the range of information to be supplied to the building official varies. Additionally, building officials are representatives of local government and may or may not recognize state or federal codes and standards. However, following methods 1 and 2 above should yield an expedited building official review because either the code recognizes SIPs outright or the manufacturer has a current certification to the building code by a third party authorized and certified to produce reports following industry and code-recognized standards (refer to Appendix C for more information on evaluations and certifications). Method 3 may or may not yield successful results in code approval, or the code official will rely solely on the professional of record's seal on the system and the design package for compliance to the code (which simply places unlimited liability on the design professional for the design, construction, and systems within a building). For these reasons, it is highly recommended that Method 3 is not used and another candidate CSIP system is chosen.

4.2.3 – CSIP Integration as a Curtain Wall

The second issue designers must consider is how CSIPs are integrated into the logistics of project deployment and construction administration. Additionally, the designer must consider how panels are manufactured to understand how they should be applied to multistory construction and how they fit into the logistics of project delivery and construction administration. In this section, constructability is a basis for understanding application design and integration into the logistics and construction administration.

The designer should understand the basic application or standards of CSIP applications in the industry. This report details this concept in several sections:

A. Section 1.5.1 – Installation of Typical Wall Panels and 1.5.2 – Construction of Weather Barrier and Window/Other Penetrations, which outline how CSIPs are used in residential construction, and
B. Section 3.2 – Classifications of Curtain Wall Systems (in general terms) and 3.6 – Proposed Wall Types and Application of CSIPs, which outline the application of CSIPs as curtain walls and the manufacturing of the curtain wall pieces.

The designer should understand the different applications of CSIPs to multistory construction as curtain walls. The only candidate application of CSIPs in multistory construction is as curtain walls because of combustibility limitations of the cores (discussed in Sections 1.7, 2.2.8.1, and 3.5). With each curtain wall system, the following design issues must be fully addressed:

- Anchor to frame details, mainly structural, which allow movement (discussed in Section 4.3);
- Intermediate frame specifications, mainly structural (discussed in Section 4.3), but also for water management details between frame and unit (discussed in Section 4.5);

- Panel system type (the selection of the CSIP type/vendor discussed in Section 4.2.1), the connection system between the panel and the frame AND panel to panel (spline type) mainly structural, the design/performance values of the panels and the assembled unit mainly structural and durability, and finishing specifications (exterior for the weather barrier and interior for the thermal barrier) (discussed in Section 4.4);
- Window unit type (and Uo Values), installation and flashing details mainly as a weather barrier (not discussed herein);
- Exterior trim type, design values, installation details, and finishing specifications (not discussed herein); and
- Construction of the totality of the unit system assembly and the completed weather barrier, thermal barriers, and seals (discussed in Section 4.5).

CSIPS can be used as curtain wall system using the Unit or Unit-Mullion System (refer to Section 3.2 for a discussion of building envelope concepts, curtain wall concepts, and the basis for deploying CSIPs as Unit and Unit-Mullion Curtain Walls). A summary below outlines the key parts of the proposed wall types:

A. Unit System: A CSIP unit system (discussed in Section 3.6.1) is comprised of units manufactured from multiple individual SIPs with a substructure or frame that bounds the units. The following parts are needed for a complete system:
    i. Panel-to-Building Anchor,
    ii. Intermediate Frame,
    iii. Panel System,
    iv. Window Units (and flashings), and
    v. Exterior Trim.
B. Unit-Mullion System: Similar to the Unit System, a CSIP Unit-Mullion System (discussed in Section 3.6.2) is comprised of units manufactured from multiple individual SIPs with a substructure or frame that bounds the units. The difference in the Unit-Mullion System is that the mullions act as an intermediary with the anchoring system, thereby creating a larger area to form a secondary seal. Additionally, a sill for water management can be installed into this mullion system for added water management. The following parts are required for a complete system:
    i. Panel-to-Building Anchor,
    ii. Vertical Mullion,
    iii. Intermediate Frame,
    iv. Panel System (and sills),
    v. Window Units (and flashings), and
    vi. Exterior Trim.

4.3 – Structural

4.3.1 – Basic Structural Requirements

Structurally, CSIP integration into curtain wall system and into multistory construction must be evaluated on various levels. Throughout this integration, the requirement of stiffness rather than strength usually governs, as excessive deformations on the exterior shell rarely lead to failure of systems other than by faulty anchorage design. Horizontal loads acting on curtain wall systems developed as wind forces acting on the building are relatively light as opposed to gravity loads or lateral loads acting on the overall building structure. The gravity loads of the curtain wall itself, however, must be considered especially as they relate to the anchorage design.

Provisions for movement must be addressed, although there is limited data on CSIP thermal movement, expansion, and vibration (this deficiency should be researched). Movement can occur on the system and individual panels through temperature changes, wind action, deformation, or displacements in the larger building frame. Movement is primarily mitigated by the detailing of the joints. Larger panels may increase the amount of movement rather than simplifying the issues; therefore, unit designs must be considered. Finally, designers must provide for both vertical and horizontal movement.

The structural design of CSIPs as curtain walls must be evaluated by the analysis of the panel properties, the analysis of the panels as a system assembly, and the analysis of the substructure to the larger building frame. Each of these analyses is described herein. All of these design procedures must be based on assumptions set forth by applicable local codes and design requirements; therefore, the professional should exercise judgment in evaluating systems. It is intended that this document be used in conjunction with competent engineering design principles, accurate fabrication and vendor technical supports, and adequate supervision and review of construction. It is always the designer's final responsibility to relate design assumptions and reference design values to make design adjustments appropriate to the end use.

The designer must apply the governing code or standard to the height of the building, the design wind pressure (referenced in Section 2.2.5, including the edge zone pressure, the pressure coefficients, etc.) and values required by seismic design procedures (referenced in Section 2.2.7).

The design and evaluation process is fluid. Candidate schematic designs should be based on CSIP curtain wall construction principles (discussed in Section 3) and Unit or Unit-Mullion Systems (as discussed in Section 3.6). This process primarily includes optimizing the panels for manufacturability and constructability. Manufacturers should be consulted early in the design process to optimize systems, to reduce costs, and to discuss the technical benefits and limitations of the manufacturer's products. However, panels in the industry are typically limited to 4'x8', 4'x10', 4'x12' nominal dimensions (width x height) and unlimited thickness dimensions. The bases of the thickness should be either the thermal performance of the curtain wall system (as defined by the baseline thickness referenced in Section 4.4.1) or the deflection criteria adopted in the project.

4.3.2 – Notation Used

The following variables will be used in the following discussion of the design process. They are listed here in order of appearance in the text.

σ = *Normal Stress*
σ_f = *Normal Stress of the Face*
σ_c = *Normal Stress of the Core*
τ = *Shear Stress*
τ_c = *Shear Stress of the Core*
M = *Bending Moment*
I_A = *Moment of Inertia*
y = *Distance from Neutral Axis of Cross-Section*
V = *Transverse Load*
Q = *Area Moment of Inertia*
t = *Thickness of Cross-Section at Point of Consideration*
P = *Axial Load*
E_c = *Elastic Modulus of Core*
E_f = *Elastic Modulus of Face*
A_c = *Cross-Sectional Area of Core*
A_f = *Cross-Sectional Area of Face*
Δ = *Total Deflection due to Transverse Load*
Δ_b = *Deflection due to Bending*
Δ_s = *Deflection due to Shear*
w = *Uniform Transverse Load*
L = *Span Length*
E_b = *SIP Modulus of Elasticity under Transverse Bending*
I = *SIP Moment of Inertia per length*
h = *Overall SIP Thickness*
c = *Core Thickness*
G = *SIP Shear Modulus*
V = *Applied Shear Force*
F_y = *Allowable Shear Stress*
C_v = *Shear Correction Factor*
M = *Applied Moment*
F_c = *Allowable Facing Compressive Stress*
F_t = *Allowable Facing Tensile Stress*
S = *SIP Section Modulus for Flexure under Transverse Loads*

4.3.3 – Analysis of CSIP Properties

First, the analysis of the individual CSIPs must be considered. This design procedure has been based on the mechanics of sandwich panels found in “APA Plywood Design Specifications Supplement 4 – Design and Fabrication of Plywood Sandwich Panels" and "The Handbook of Sandwich Construction." [54, 55] This analysis is limited to the individual panel area through load diagrams, deflection diagrams, and stress diagrams. A competent engineer should follow the design principles he or she is most familiar and comfortable with and contact vendor technical support before finalizing drawings, reviewing shop drawings, or starting construction. The analysis of the CSIPs is based on the following steps:

GOAL: validate the CSIP to the <u>design pressures acting on the panels—check against deflection, shear, and bending of facings.</u>

A. Draft a schematic diagram of the proposed design for the curtain wall system, including individual CSIPs, substructures, and supports to the building frame.
B. Evaluation of Load Cases: The following procedure should be used for each of the defined load cases (defined in Sections 4.3.3C and 4.3.3D).
    a. Use the design loads determined by the construction of a <u>loading diagram and referenced loading pressure</u> to apply forces on the CSIP;
    b. Transverse Panel Analysis: Using the generated loading diagram (Section 4.3.3A), generate a deflection diagram to determine the <u>maximum deflection of the individual CSIPs</u>. Check to ensure the maximum deflection is acceptable with the deflection mode of the panel (i.e., that the maximum deflection is occurring in regions where the deflection was determined by ASTM E72 tests as discussed in Section 2.4). For example, if this is uniform across the panels, typically the maximum deflection is at the centroid of the panel.
        i. Check the deflection of the simply supported panel under uniform transverse load of the CSIPs, given

$$\Delta = \Delta_b + \Delta_s = \frac{5wL^4 \times 1728}{384E_b I} + \frac{wL^2}{4(h+c)G}$$

so the total deflection shall not exceed L/180, the limitations of the building code, or recognized minimum design standards dictated by:

Maximum Design Bending Load / Allowable Bending Load <= 1

    c. Shear Stress Panel Analysis: Using the generated loading diagram (Section 4.3.3A), generate a stress diagram to determine the <u>maximum stress acting on the individual CSIPs</u>. Check to ensure the maximum stress is acceptable with the allowable stress of the panel.

[54] "APA Plywood Design Specifications Supplement 4 – Design and Fabrication of Plywood Sandwich Panels" (Document U814-H, March 1990).
[55] Zenkert, D. "The Handbook of Sandwich Construction". Published by Engineering Materials Advisory Services, 1997.

i. Check that the maximum panel shear stress is less than the allowable shear stress, given

Maximum Design Stress / Allowable Stress <=1

ii. Check that panel shear strength under transverse loading also satisfies

$$\frac{V}{6(h+c)} \le F_v C_v ,$$

given the following shear adjustment factors C_v of the intended support diagrams below:

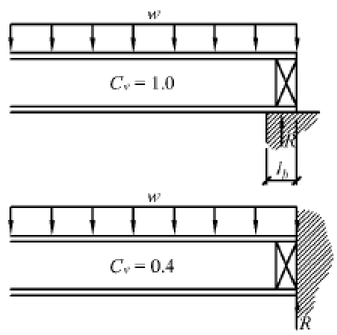

Figure 53 – Support Conditions [56]

Note: for other loading and support conditions, consult the panel manufacturer.

d. Bending Flexure Panel Analysis: Use the generated loading diagram and section properties (Section 4.3.3A) to satisfy the following equation for <u>evaluation of facing materials,</u> given

$$M \le F_t S$$
$$M \le F_c S$$

C. Evaluation of Static Load Cases: follow ASCE 7 as referenced in Section 2.2.5 to determine safety factors, load combinations, building height, wind pressure, pressure coefficients, and design wind pressure, and follow the evaluation of load cases above (Section 4.3.3B) with the supplied information.

D. Evaluation of Impact Load Cases: follow ASCE 7 or local codes to determine the <u>impact load combinations acting on the individual CSIPs</u>. Generate cases and use the evaluation of load cases above (Section 4.3.3B) to evaluate the loading diagram (Section 4.3.3B.a), maximum deflection (Section 4.3.3B.b), maximum stress (Section 4.3.3B.c), and bending flexure (Section 4.3.3B.d) for

[56] Courtesy SIPA

the different impact load combinations to determine the maximum deflection, shear stress, and bending flexure for the impact loads.

E. The maximum deflection, shear stress, and bending flexure govern the design basis for the individual CSIPs from the static load case and the impact load case. If the allowable loads for each are greater than the design loads, proceed to Section 4.3.4, else review design assumptions or schematic design and modify the proposal to return to Section 4.3.3.

4.3.4 – Analysis of Panels as a System

Secondly, the analysis of the curtain wall unit and substructure members must be considered. This design procedure has been based on simple mechanics of beams. This analysis is limited in this step to the members of the substructure through load diagrams, deflection diagrams, and stress diagrams. A competent engineer should follow the design principles he or she is most familiar and comfortable with and contact vendor technical support for final consultation prior to finalizing drawings, reviewing shop drawings, or starting construction. The analysis of the curtain wall unit and substructure is based on the following steps:

GOAL: validate the curtain wall unit and substructure to the tributary areas and <u>resulting forces and transfer of forces to the building frame acting on the members to check against moment, deflection, and shear.</u>

A. Take the draft of the schematic diagram for the curtain wall system including CSIPs, substructure, and supports to the building frame. Use simple engineering mechanics to evaluate the static structural analysis of the simple beam members and verify the substructure frame.
B. Calculate the tributary area of the support member and draft the support conditions of the vertical members (which may be modeled as individual or continuous beams given the design parameters). Nodes will occur at the joint where the curtain wall members tie into the building frame, mullions, and other subsequent substructure members. At the completion of this step, the designer should have beam diagrams to determine the model criteria, node coordinates, node restraints, member releases, and section properties for the members.
C. Evaluation of Load Case: The following procedure should be used for each of the defined load cases (defined in Section 4.3.4D).
    a. Use the design loads determined by the construction of a <u>simple structural beam diagrams and referenced load cases</u> to apply forces on the members;
    b. Transverse Panel Analysis: Using a loading diagram, generate a deflection diagram to determine the <u>maximum deflection of the members</u>. Check to ensure the maximum deflection is acceptable, given

       Maximum Design Deflection < Allowable Deflection

    c. Moment Analysis: Using a loading diagram, generate a moment diagram to determine the <u>maximum moment in the members</u>. Check to ensure the maximum moment is acceptable, given

Maximum Design Moment < Allowable Moment

d. Shear Stress Panel Analysis: generate a deflection diagram to determine the <u>maximum deflection of the members</u>. Check to ensure the maximum deflection is acceptable, given

Maximum Shear Stress < Allowable Shear Stress

e. Node Reactions: record the node reactions for each of the load cases for use in anchorage design discussed in Section 4.3.5.

D. Evaluation of Static Load Cases: follow ASCE 7 to determine the safety factors, load combinations, and load cases and follow the evaluation of load cases above (Section 4.3.4C) with the supplied information and tributary areas (determined in Section 4.3.4B) for the member supports.
E. The maximum deflection, moment, and shear stress govern the design basis for the individual CSIPs from the static load cases. If the allowable loads for each are greater than the design loads, proceed to Section 4.3.5, else review design assumptions or schematic design (member's section properties or materials) and proceed to Section 4.3.4 or review the schematic design of the entire system and proceed to Section 4.3.3.

4.3.5 – Analysis of Substructure to the Building Frame

The analysis of the transfer of loads from the frame to the building frame is not outlined within this design guide. Common curtain wall designs of anchors can be used to tie CSIPs to the building frame. Node reactions from the analysis of the substructure (outlined in Section 4.3.3) are used for the basis of the design by the structural engineer for the building frame to calculate the support bracket loads and reactions, anchor bolt sizes and placement, and other issues.

Facade engineers can be consulted to determine the best anchorage method and optimization of the installation given whole building delivery. However, the results obtained from the processes above will be used in the determination of adequate systems for transferring the loads into the building frame and should be discussed with the facade engineers or structural engineer designing the building frame.

4.3.6 – Seismic Design

Although a general procedure for analysis is noted in Section 2.2.7, the current building code (assumed to be 2006 IBC) does not allow a designer to account for the added structural robustness of CSIPs to resist lateral loading in their design of the building. This is solely due to the limitations dictated by the fire code—in particular, that all structural members must be noncombustible for multistory construction (refer to Section 2.2.7.1 for a general discussion). Because the core of the CSIP is polymer based, its relative melting point to these other members will be significantly lower and unsafe for consideration.

The 2006 IBC indicates in Section 714 the protection of "other structural members" should follow that of columns, girders, trusses, beams, and the like. In particular, section 714 points out that seismic isolators, for example, must follow the fire rating of the columns as dictated in Table 601 and that that the isolator must work the same after the fire as before the fire (i.e., after recovery). After CSIPs have been exposed to high heat—not even a flame—most, if not all, of their ability to resist lateral loading will be severely diminished. Additionally, the connection between the building, substructure, and the CSIPs have not been optimized or thoroughly tested to resist and transfer lateral loads. Both of these topics are further research areas the industry should address. For these reasons, SIPs should not currently be considered to carry or transfer lateral loads in curtain wall assemblies.

Further research should also investigate the use of alternative insulation cores, which may not have the combustibility limitations and which may allow CSIPs to be used as wall panels and lateral loading devices.

4.4 – Optimizing the Thermal Envelope

The energy saving potential of building with CSIPs is the most apparent sustainable advantage of utilizing CSIPs as curtain walls (as discussed in Section 2.3.1). A CSIP building envelope provides high levels of insulation and is extremely airtight. This means significantly lower operating costs for an owner as well as a smaller contribution to the energy use and carbon emissions from your building. Energy Flow-through building panels and wall assemblies are primarily driven through two mechanisms:

1) Temperature-driven heat transfer through conduction and radiative heat transfer. Conduction involves heat traveling through a solid material, and radiative heat transfer is the movement of heat energy through space without relying on conduction through the air or by movement of air, and
2) Air Infiltration through convection (the transfer of heat by the movement of gases or liquids through a system)

Temperature-driven heat transfer is the differential between the inside and outside temperature—heat is either lost or gained through the section, frame, and panels. This is indicated in terms of the U-factor or R-factor of the assembly (U=1/R). Infiltration of heat lost or gained is indicated by the air infiltration through cracks in the assembly. This negative effect is measured in terms of amount of air that passes through a unit area of the panel under different pressure conditions. Infiltration is thus driven by wind-driven and temperature-driven pressure changes and fluctuations. Infiltration may also contribute to interior humidity.

The following areas must be optimized:

- Baseline Panel (CSIP Thickness),
- Substructure Joints (CSIP to Unit boundaries and Unit to Unit connections),
- Spline Joints (CSIP to CSIP Connections), and
- Penetration Joints (CSIP to Penetrating Unit Connections).

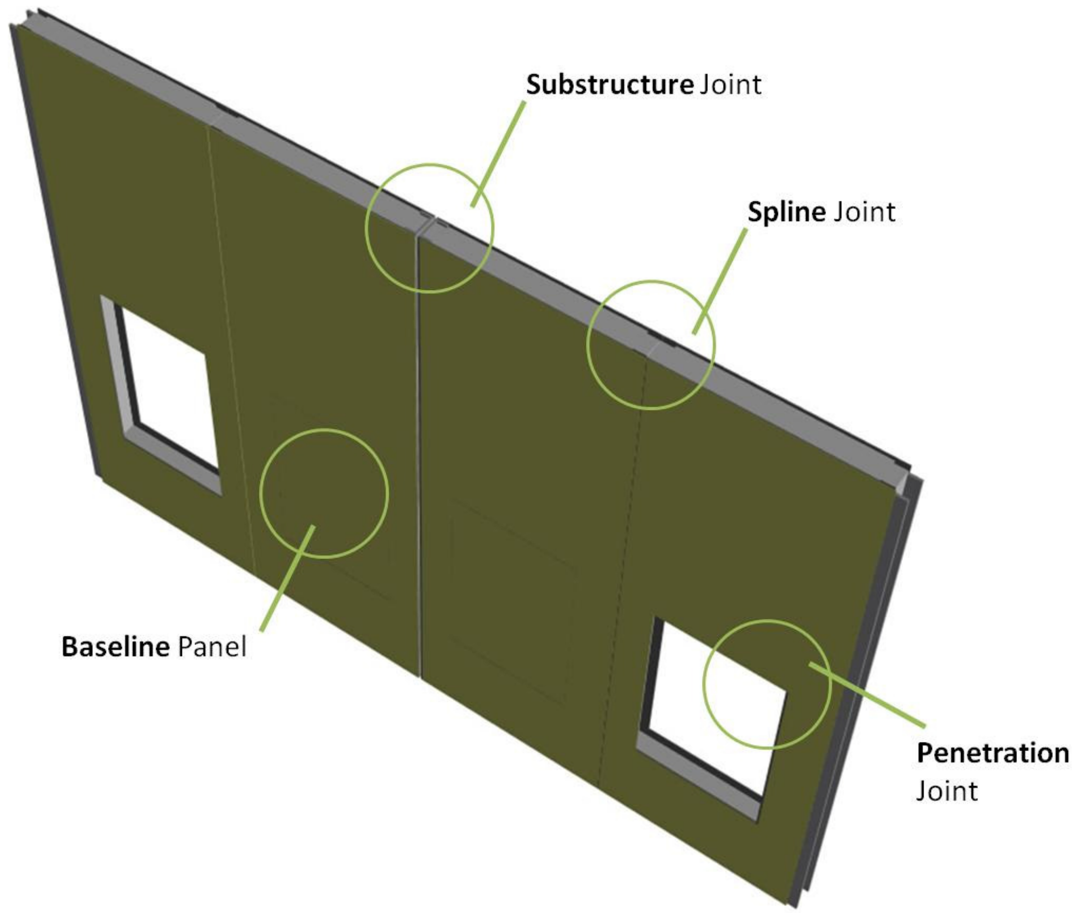

Figure 54 - Typical Joint Locations for Thermal Optimization

For a discussion of panel optimization refer to Figure 27 – Relative Thermal Performance of SIP Connection Types in Section 2.3.3.1 and consult note that each manufacturer and project will have specific details that require selection, analysis, modeling, and optimization.

4.4.1 – Determine a Baseline Panel Thickness

Baseline thermal performance is based on the insulation core's thickness. Not all CSIPs have the same thermal performance because of the materials used and the construction standards. CSIPs can be made thicker with more insulation, having a higher insulating value (R-value), and transferring less heat, depending on the spline conditions. However, it is not enough to judge their effective thermal performance by simply noting this R-value. This assumes a wall is entirely filled with insulating material and makes for a poor and misleading comparison of building systems.

This improved performance of SIPs is confirmed in a study of whole-wall R-values conducted by the Oak Ridge National Lab. The study accounts for heat loss through windows, doors, corners, and slab connections. The results demonstrate the benefits of SIPs—the lack of thermal shorts creates a higher whole-wall R-value than conventional wood-framing construction.

The selection must be based on the insulation type from various vendors. There are three key insulation types: EPS foam, XPS foam, and polyurethane. Their insulation values are primarily based on their relative density. This is a linear relationship throughout the assembly. Therefore, given the thermal conductivity of the insulation per inch (expressed as its U-value or R-Value (R-Value = 1/U-Value), designers can easily calculate the baseline required panel thickness required by code, the building owner, or by other needs. Listed below are the most common insulation cores in the SIP industry. However, manufacturers should supply specific materials testing information on the cores.

EPS = 4.0 R/Inch

Polyurethane = 6.7 R/Inch

XPS = 5.4 R/Inch

WARNING: there are minimum standards for insulation in the respected insulation industries based primarily on density. Manufacturers have been known to advertise higher densities, and higher R-values, for insulation cores and then deliver panels with cores of substantially lower densities. It is very difficult to determine the insulation density after lamination and verify it on an ongoing basis. Therefore, it is highly recommended that designers use the minimum insulation values in their assumptions to prevent this issue.

4.4.2 – Optimizing Splines, Connections, and the Boundary Conditions

Most building systems have small conductive elements that penetrate or go around the insulation to create thermal bridges—"short circuits"—through which heat can travel. Thermal bridges significantly lower the effective insulation value and create unanticipated temperature gradients that can lead to thermal stress, condensation, and other effects. Therefore, designers must be very critical of the connections and methodologies to make the connections (i.e., connection type vs. the effects on the thermal conductivity of the panel given the connection type).

Because SIPs are a system assembly, almost a kit of parts, it is easy to evaluate temperature-driven heat transfer and infiltration simultaneous simply because all infiltration points are also points where direct temperature-driven heat transfer is applied. These locations are confined to the perimeter or boundary of the panels. Therefore, we must consider constructability, weatherization, and thermal barriers as well as spline condition, type, and so forth. To accomplish this, FAS modeled the different panel connection types to determine the preferred designs.

The following spline conditions were modeled in THERM (detailed in Section 2.3.3.1) and modeled as a physical assembly (showing the fiber-cement siding (green), EPS (gray), and metal sections (purple)). Also, the infrared analysis showing heat transfer through the assembly and the gradations are illustrated. The infrared sections help illustrate areas where heat flow is greater than the baseline.

Gradual, defined, and uniformed gradations are ideal. For all assemblies, the calculated R-value is given and the percent error in the solution.

Typological Connection Type & Relative Performance

	U-factor	R-factor	Error
Blank panel (baseline)	0.0400	25.00	0.00%
Assumed baseline panel			
Wood Surface Spline	0.0416	24.04	1.70%
Metal Surface Spline	0.0430	23.26	4.50%
Preferred panel to panel connection.			
Full Wood Spline	0.0580	17.24	1.20%
Full Metal Spline	0.1752	5.71	7.95%
Guarded Metal Tube	0.0862	11.60	6.53%
Guarded Metal Solid	0.0870	11.49	6.56%
Preferred substructure panel connection.			
Metal Offset Spline	0.1154	8.67	7.61%
Guarded Metal Offset Spline	0.0709	14.10	8.99%
Preferred substructure panel connection.			

Note: assume 5.5" insulation core throughout.

Figure 55 - Relative Thermal Performance of CSIP Connections

These splines are for illustrative purposes only. After the structural design is complete, the designer should use THERM in critical conditions (i.e., panel to panel (plan), panel to building (plan and section) and other penetrations, connections, and boundaries to determine if the materials are optimized).

The performed thermal analyses are general in nature, and it is recommended that each project run specific evaluations, for the thermal analysis has varying section moduli and areas.

FAS has based thermal performance calculations on the finite-element analysis of a steady-state, two-dimensional heat transfer software. Once a cross section's geometry, material properties, and boundary conditions are defined in the program (all known quantities in a wall assembly), THERM meshes the cross-section, performs the heat-transfer analysis, runs an error estimation, refines the mesh if necessary, and returns the converged solution.[57] These results show more than just the R-value of the insulating components. They allow the user to evaluate a building component's energy efficiency and local temperature patterns, demonstrating the effective thermal performance of the entire assembly. We recommend using THERM to evaluate any final design to ensure "thermal shorts" are kept at a minimum.

THERM is an easy method for optimizing joints. Engineers should engineer structural components then model joints and connections for both structure and heat flow.

[57] More information on how THERM works can be found at FROM LBL WEBSITE.

WARNING: There are some limitations to the current details in the industry. Wall details are primarily derived from residential construction and may need further modification for commercial use given construction/material handling. Wall details are adapted from standard practice and may not be optimal in terms of balancing the infiltration, heat transfer, and constructability. Overall, more research is needed in splines and optimum splines/connectors.

4.4.3 – Estimation of Thermal Wall Efficiencies Using a Weighted Area Technique for SIP Applications by Optimizing CSIP Details for Efficient Curtain Walls

Assumptions:

1. The wall "thickness," whether known or unknown, is constant over the panel area;
2. All the "R-Values" of connections, conditions, and joints (including splines, tracks, and end conditions) are known (i.e., based on industry standards or provided by manufacturers' through testing) or can be approximated by utilizing THERM; and
3. Penetrations, all window and door assemblies, are ignored and are considered outside the scope of this estimation. To evaluate window and wall efficiencies given climate, orientation, use, etc., please use DOE-2 or equivalent software and analysis for whole building designs.
4. Estimation of connections, splines, and other common details is known (preferred) or can be approximated using linear proportionality given insulation type, R-value, thickness or connection type, R-value, or thickness.

If the designers know or have been provided the thickness of the wall panel and the respected R-values for the connections, conditions, and joints to be used, the following procedure applies. Given the following specification:

> *Specification: a <u>curtain wall unit</u> constructed of 4x10 CSIPs, a 1.5" guarded metal offset end member, a 3" full metal spline, and 6" metal surface spline. The manufacturer has provided the theoretical R-values using THERM for the connections: Metal Surface Spline = 23.26, Full Metal Spline = 5.71, and Guarded Metal Offset Spline = 14.10. The manufacturer has recommended a panel thickness of 6" at R=25. An architectural rendering and elevations are provided below.*
>
> *Question: is a nominal 6" panel (5.5" of EPS) thick enough if the design R-value is R22?*

a. Diagram the wall assembly:

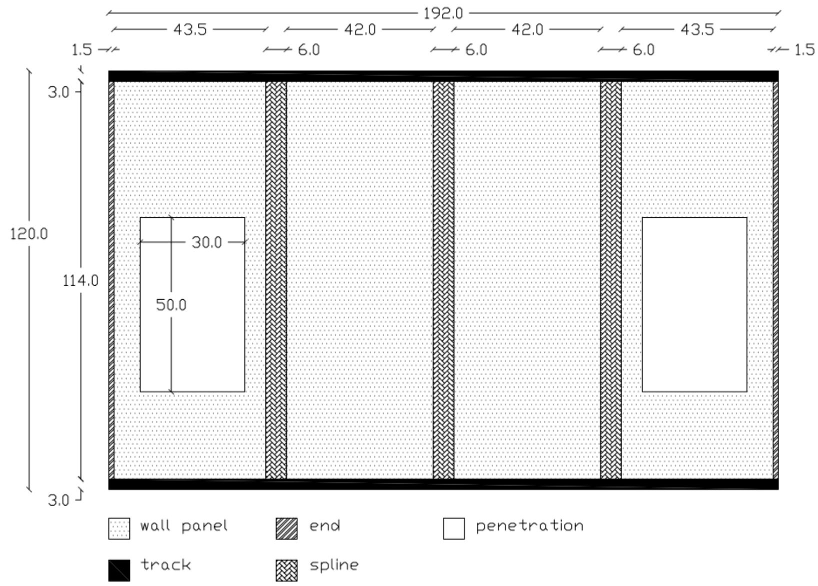

Figure 56 - Panel Shop Drawings/Engineering Drawings

b. Calculate the following areas (in inches):

   a. $A_{gross} = h*w = 120 * 192 = 23040\ in^2$
   b. $A_{penetrations}$= Sum $((h_{p1} * w_{p1}) + ... (h_{pn}*w_{pn})) = (50 * 30) + (50 * 30)=3000\ in^2$
   c. $A_{net} = A_{gross} – A_{penetrations} = 20040\ in^2$
   d. $A_{connections}$ = Sum $((A_{spline}) + (A_{track}) + (A_{ends})) = 2052 + 1152 + 342 = 3546\ in^2$ where,
      i. A_{spline} = Sum $((h_{s1} *w_{s1}) + ... (h_{sn}*w_{sn})) = 3 * (6 * 114) = 2052\ in^2$
      ii. A_{track} = Sum $((h_{t1} * w_{t1}) + ... (h_{tn} * w_{tn})) = 2* (3 * 192) = 1152\ in^2$
      iii. A_{ends} = Sum $((h_{e1} * w_{e1}) +... (h_{en} * w_{en})) = 2*(1.5 * 114) = 342\ in^2$
   e. $A_{wall} = A_{net} – A_{connections} = 20040 – 3546 = 16494\ in^2$

c. Determine or look up the R-values (per assembly section (in K·m²/W)) of each condition:

   a. Wall Area: R_{wall} = Baseline Panel R-Value = 25 (Blank Panel)
   b. Connections. Using tables provided by the manufacturers, calculated using THERM or laboratory tests, or following industry standards, evaluate the connection efficiencies:
      i. R_{spline} = Spline Joint R-Value = 23.26 (Metal Surface Spline) = R_{max}
      ii. R_{track} = Substructure Joint R-Value (horizontal run) = 5.71 (Full Metal Spline) = R_{min}
      iii. R_{ends} = Substructure Joint R-Value (vertical run) = 14.10 (Guarded Metal Offset)
      iv. Average $R_{connections} = (R_{spline} + R_{track} + R_{ends})/3 = (23.26 + 5.71 + 14.10) / 3 = 14.4$
      v. Note, Min and Max R-value of connections as R_{min} and R_{ma}x
         1. R_{max} = Metal Surface Spline = 23.26

2. R_{min} = Full Metal Spline = 5.71

d. Estimate the Ideal (Weighted Area) = $R_{wall} * A_{net}$ = 25 * 20040 = 501000

e. Quick Calc:
   a. Upper Bound Quick (Weighted Area) Efficiency =
      $((R_{wall} * A_{wall}) + (R_{max} * A_{connections}))$ / (Ideal) =
      ((25 * 16494) + (23.26 * 3546)) / (501000)= 0.988 = 99%
   b. Quick (Weighted Area) Efficiency =
      $((R_{wall} * A_{wall}) + (R_{connections} * A_{connections}))$ / (Ideal) =
      ((25 * 16494) + (14.4 * 3546)) / (501000)= 0.925 = 93%
   c. Lower Bound Quick (Weighted Area) Efficiency =
      $((R_{wall} * A_{wall}) + (R_{connections} * A_{connections}))$ / (Ideal) =
      ((25 * 16494) + (5.71 * 3546)) / (501000) = 0.863 = 0.86%
   d. Estimate Error = (Upper Bound - Lower Bound)/2 =
      (0.988-0.863) / 2 = 0.0625 = 6.25%

   Therefore, the Quick Calculation is 93% +- 6.25%

f. Wall (Weighted Area) Efficiency =
   $W_{eff} = ((R_{wall}*A_{wall}) + (R_{spline}*A_{spline}) + (R_{track}*A_{track}) + (R_{ends}*A_{ends}))/(Ideal)$ =
   ((25 * 16494) + (23.26 * 2052) + (5.71 * 1152) + (14.10 * 342) / (50100)=.941 = 94%

g. Ratios:
   a. Window : Wall Ratios = $A_{penetrations}/A_{net}$ = 3000 / 20040 = 0.150 = 15%
   b. Connection : Wall Ratios = $A_{connections}/A_{net}$ = 3546 / 20040 = 0.177 = 17%
   c. Potential Infiltration : Wall Ratio (Risk) = $(A_{penetrations} + A_{connections})/A_{net}$ =
      (3000 + 3546) / 20040 = 0.327 = 33%

h. Estimated (weighted average) Whole Wall R-value = $W_{eff} * R_{wall}$ = 0.941 * 25 = 23.525

Therefore, the estimated wall efficiency of this design (excluding penetrations, doors, and windows) is 94% using a weighted average approach. Likewise, the estimated Whole Wall R-value of the assembly is 23.525 using a baseline 6" panel, which has an R-value of 25. The window to wall ratio is 15% and the connection to wall ratio is 17%, giving a potential risk for infiltration by these factors 33%.

Note: Ultimately, the connection dimensions are determined from the structural analysis, but the designers should use the thermal analysis as a method of evaluation to ensure the designs are thermally efficient.

Design Procedure: Proposing a Design

To propose a design for analysis, the designer must make initial assumptions and provide allowances for future optimization. In this process, the designer will be given a target whole wall design value and be asked to detail the curtain wall assembly. The following steps should be followed:

> *PROBLEM: Design a CSIP curtain Wall unit with a whole wall R-value of* 20 (R_{Target}=20) and *check the wall's efficiency and window: wall, connection: wall, and potential infiltration: wall Ratios.*

a. Diagram the wall assembly and give 6" allowances for all connections:

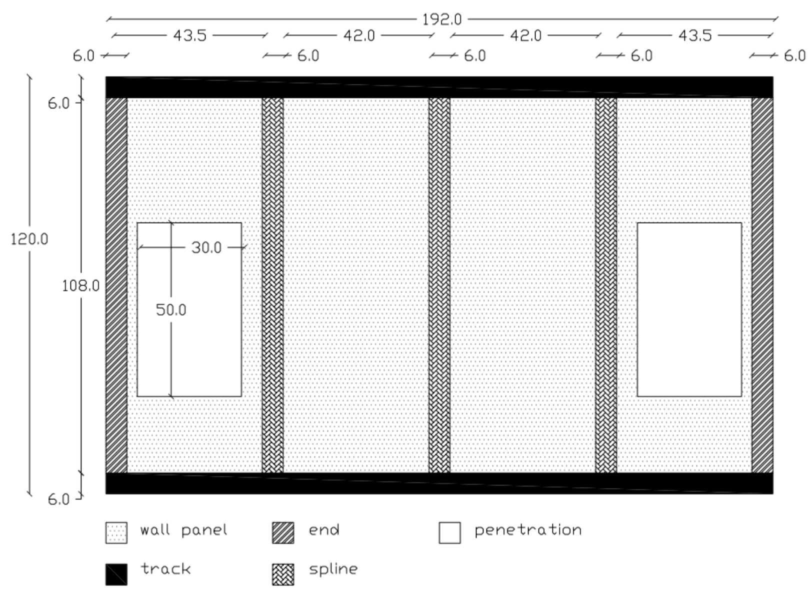

Figure 57 - Diagrammed Wall Assembly

b. Calculate the following areas:
   a. A_{gross} = h * w = 120 * 192 = 23040 in^2
   b. $A_{penetrations}$= Sum ((h_{p1} * w_{p1}) + … (h_{pn}* w_{pn})) = (50 * 30) + (50 * 30)=3000 in^2
   c. A_{net} = A_{gross} – $A_{penetrations}$ = 20040 in^2
   d. $A_{connections}$ = Sum ((A_{spline}) + (A_{track}) + (A_{ends})) = 2052 + 2304 + 1296 = 5652 in^2 where,
      i. A_{spline} = Sum ((h_{s1} * w_{s1}) + … (h_{sn}* w_{sn})) = 3 * (6 * 114) = 2052 in^2
      ii. A_{track} = Sum ((h_{t1} * w_{t1}) + … (h_{tn} * w_{tn})) = 2 * (6 * 192) = 2304 in^2
      iii. A_{ends} = Sum ((h_{e1} * w_{e1}) +… (h_{en} * w_{en})) = 2*(6 * 108) = 1296 in^2
   e. A_{wall} = A_{net} – $A_{connections}$ = 20040 – 5658 = 14382 in^2

c. Make assumptions about initial connection types:

a. Connections: Initially choose the connections for the splines by referring to manufacturer's data or charts to determine the reduction factors OR estimate the performance based on a quick calculation:

   i. For this example, use the table below to find the reduction factors…

      1. R_{spline} = Spline Joint R-Value = Metal Surface Spline = 0.93R = R_{max}
      2. R_{track} = Substructure Joint R-Value (horizontal run) = Full Metal Spline = 0.23R = R_{min}
      3. R_{ends} = Substructure Joint R-Value (vertical run) = Guarded Metal Offset = 0.56R
      4. Note, Min and Max R-value of connections as R_{min} and R_{max}

   ii. Estimating the performance based on a quick calculation…

      1. if insulation thickness > 0, then $R_{connection}$ = Insulation Thickness * R-value of the insulation = $t_{insulation}$ * $R_{insulation}$
      2. if insulation thickness < 0, then Rconnection = Connection Thickness * R-value of the connection = $t_{connection}$ * $R_{connection}$

d. Determine baseline R-value of wall panel given connection reduction, by solving for R:

   i. Anet * R_{Target} = (R_{wall} * A_{wall}) + (R_{spline} * A_{spline}) + (R_{track} * A_{track}) + (R_{ends} * A_{ends}) =
   20040 * 20 = (R * 14382) + (0.93R * 2052) + (.23R * 2304) + (.56R * 1296)
   400800 = 14382R + 1908.4R + 529.9R + 725.8R
   400800 = 17543.1 * R
   R=22.84

   ii. Given, R = $t_{insulation}$ * $R_{insulation}$, solve for $t_{insulation}$

      1. $t_{insulation}$ = R / $R_{insulation}$
      $t_{insulation}$ = 22.84 / 4.55 per inch = 5.02" EPS Core, OK Use 5" EPS

e. Wall (Weighted Area) Efficiency:

   a. Estimate the Ideal (Weighted Area) = R_{wall} * A_{net} = 22.84 * 20040 = 457713.6
   b. Wall (Weighted Area) Efficiency:
   ((R_{wall} * A_{wall}) + (R_{spline} * A_{spline}) + (R_{track} * A_{track}) + (R_{ends} * A_{ends})) / Ideal =
   ((R * 14382) + (0.93R * 2052) + (0.23R * 2304) + (0.56R * 1296)) / 457713.6
   ((22.84 * 14382) + (0.93(22.84) * 2052) + (0.23(22.84) * 2304) + (0.56(22.84) * 1296)) / 457713.6
   (328485 + 43587 + 12103 + 16576) / 457713.6 = 0.876 = 88%

f. Ratios:

   a. Window : Wall Ratios = $A_{penetrations}$ / A_{net} = 3000 / 20040 = 0.150 = 15%
   b. Connection : Wall Ratios = $A_{connections}$ / A_{net} = 5652 / 20040 = 0.282 = 28%
   c. Potential Infiltration : Wall Ratio = ($A_{penetrations}$ + $A_{connections}$) / A_{net} =
   (5652 + 3546) / 20040 = 0.459 = 46%

Note: the low wall efficiency, high connection to wall ratio, and very high infiltration risk ratio would lead us to believe the connection allowances are generally too big and should be scaled back. Ultimately, the connection dimensions are determined from the structural analysis, but the designers should use the thermal analysis as a method of evaluation to ensure the designs are thermally efficient.

In general, this method for whole wall R-value approximation needs validation, either computationally or through physical testing. Industry standards should develop a process for both. Manufacturers should individually generate the data for their products or test the materials/connections.

The central goal in the design is to maximize the whole wall R-value. Therefore, connections should be studied, quantified, and analyzed. Additionally, all penetrations will determine how well the proposed design ultimately meets the intended design. This concern is captured in the potential infiltration: wall ratio in which the lower the number, the less constructability issues come into play to meet the design intentions.

4.4.4 – Building Tightness

There is no easy way to calculate and design for building tightness prior to final finish because it ultimately relies on the specifications and quality of installation. The tightness is ultimately determined by the seals between the panels, panels to building, and all the penetrations that can be evaluated after the building is constructed through similar testing methods as the blower door test. This hinges on the weather barrier test for the panel systems, and bases the assumptions on physical tests, mock ups, and prototypes. Please refer to Section 4.5 – Waterproofing for relevant information about exterior treatments to reduce air infiltration.

Other factors that affect building tightness are interior seals, caulks, and other treatment of interior finishes, trim, and interactions between the two that close gaps, cracks, and imperfections in the construction. Typically, this is a surface control measure paint and caulk control.

The proper use of flashing and counter-flashing can minimize air infiltration, as well as properly installing window units and preparing openings and penetration for controlled passage. The installation of windows into the panels is outside the scope of this document, as it is clearly manufacturer-specific, but each penetration should be prepped with an elastomeric pan flashing, jamb flashing, and header flashing followed by the installation of the window with proper sealants and mechanical fastening to the blocking in the CSIP. These details may require windows with exterior flanges, but they promote proper drainage and evacuation of water to the exterior. Counter-flashing should be installed, and as required, materials to create and maintain a drainage cavity should be installed between the counter-flashing and exterior window trim. These layers of redundancy and control allow localized drainage cavities to be built up around penetrations while relying on the flashing materials to channel excess water to the exterior. Any moisture saturated in the wall assembly can dry out given that the exterior and interior facing materials should be more permeable than the interior core material. Typical window and wall details for penetrations are illustrated in Sections 1.5.2 and 3.6.1.1, but they have so far been limited to residential construction.

WARNING: The professional of record must consider the following:

- *The degree of building tightness capable in CSIP construction better enables mechanical ventilation to filter allergens and dehumidify air. Additionally, the tightness and the thermal insulation together can reduce the loads on the mechanical system.*
- *This ultimately hinges on the visual inspection that all interior and exterior seams are properly sealed with expanding foam or manufacturer-approved sealing mastic or tape to create an uninterrupted barrier between the panels.*
    - *The inspection must also check that sills, penetrations, and ties into the floor and substructure are flush or caulked to the panel—preferably directly to the foam core if possible.*
    - *The inspection should also ensure all through-wall penetrations such as passage, windows, HVAC duct work, electrical wiring, and plumbing have been sealed properly and scrap insulation or foam seal has been used to fill voids.*
- *The mechanical contractors should be notified that a full Manual-J calculation should be used to evaluate the mechanical system and proper commissioning of the mechanical system, and balancing, is necessary to sustain proper ventilation rates, comfort, and required fresh air exchanges.*
    - *Commissioning of the mechanical system and all other systems in the building should be performed to optimize the energy efficiency of the building.*

4.5 – Waterproofing and Detailing

Waterproofing is best controlled through proper detailing of assemblies to ensure that water has an unbroken barrier to escape any joint, infiltration area, or crack in the system. Water penetration resistance is a function of substructure construction, drainage details, water management control (weather stripping, gaskets, and sealants), and flashing/counter-flashing of all windows, penetration, etc.

To understand the design issues, first we must discuss the mechanisms that move water into the building: gravity, kinetic energy, pressure gradients, surface tensions, and capillary action. Because CSIP wall units are built up from monolithic sandwich panels, more perimeter lengths must be properly designed, detailed, and constructed to ensure proper water management and water shed to the building's exterior. This allows the designer to be cautious and conservative about water management details while focusing the main concern on water management between units and at unit corners. Both Unit and Unit-Mullion curtain walls allow a great deal of flashing integration into the manufactured assemblies and proper ties of this flashing into the building's frame.

These joints, which need proper waterproofing and detailing, are also areas where durability and maintenance must be discussed. All joints using weather stripping, gaskets, and sealants have service life expectancies and maintenance requirements. Durability problems include damage due to movement, prolonged exposure to water, UV degradation, and age. Designers should consider how repairs would be made to the system so that the entire unit or assembly does not have to be removed or dismantled. Repairs should require exterior access only. Recommendations for designs include:

Basic Design and Detailing Principles:

i. Diagramming all details, sections, and plans to illustrate the unbroken path of water movement and drying back to the exterior;
ii. Managing the drainage of individual units on their unit scale (not multiple units shedding on lower levels);
    - Limited horizontal mullions or requiring all horizontal mullions as sills;
    - Using vertical mullions (in Unit-Mullion Systems) as vertical channels for water management; and
    - Substructure frames with wept glazing and sloped sills to promote proper drainage.
iii. Internal drainage methodologies may be used where minor leakage is assumed to be permitted at all exterior surfaces as long as drainage paths and flashing and collection mechanism for managing infiltrated water into the cavities is provided.
    - Cavities between caulks and sealants to promote pressure equalization in cavities and should include weep holes and water catchers;
    - All joints and boundary conditions between units or between penetrations in panels should be treated like pressure-equalized cavities in which the back interior surface is sealed and the cavity between the inner and outer surface is allowed to vent while still allowing positive drainage to the exterior.

WARNING: The professional of record must consider the following:

- *The degree of building tightness capable in CSIP construction better enables mechanical ventilation to filter allergens and dehumidify air. Additionally, the tightness and the thermal insulation together can reduce the loads on the mechanical system.*
- *This ultimately hinges on the visual inspection that all interior and exterior seams are properly sealed with expanding foam or manufacturer-approved sealing mastic or tape to create an uninterrupted barrier between the panels.*
    - *The inspection must also check that sills, penetrations, and ties into the floor and substructure are flush or caulked to the panel—preferably directly to the foam core if possible.*
    - *All through-wall penetrations such as passage, windows, HVAC duct work, electrical wiring, and plumbing have been sealed properly and scrap insulation or foam seal has been used to fill voids.*

4.5.1 – Specific Control Measures

A. Moisture and Condensation Control:

Moisture management is less of an issue with closed wall panels if the facing materials are more permeable than the core material. This management principle will allow any water to dry out of the core material (and more importantly the lamination line). Therefore, the designer should be concerned with the perm ratings of all facing materials and exterior finishes. As long as the perm rating of the facings is less than the core, condensation control may not be required.

B. Rain Penetration Control:

Rain penetration control can be managed by localized drainage planes and spaces around all splines, penetration, and within the window details. Good drainage plane and drainage space methodology by localizing the planes and spaces of the penetrations are required to promote positive drain action within this space.

All joints and boundary conditions between units or between penetrations in panels should be treated like pressure-equalized cavities in which the back interior surface is sealed (5) and the cavity between the inner and outer surface is allowed to vent while still allowing positive drainage to the exterior; the outer cavity is maintained by the installation of a gasket seal with weeps (6). This drainage should be facilitated by horizontal flashing of the unit at the sill that drains water to the exterior or collects water to the vertical mullion, which may act as a vertical gutter.

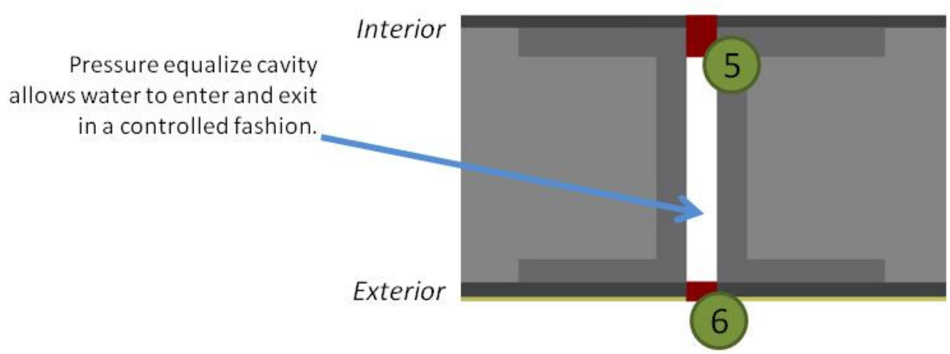

Figure 58 - Pressure Equalized Cavity

This rain penetration strategy must be understood on three different areas: Unit joints, CSIP Spline Joints, and Penetrations (refer to Section 3.2 for review of weatherization details).

i. At Wall Unit Joints:
   a. Ensure that sill and rain catcher is properly installed at unit base;
   b. At all joints, use impervious caulk at the interior plane accessed through the exterior of the building;
   c. Tool the caulk with a round-tipped tool to ensure proper adhesion to surfaces (creating unbroken drainage plane);

d. Use gasket installation tool to install gasket within the unit joint to enclose the cavity (creating the drainage space);
e. Allow for proper weep holes to evacuate the excess water in the cavity to the exterior; and
f. Ensure the excess water is caught and shed or drained to a control measure that doesn't shed the water on subsequent panels (such as vertical mullions in the Unit-Mullion System).

ii. At Splines: (follow weather barrier details per manufacturer's instructions (discussed in Sections 1.5.1 and 3.2)). This should include:
   a. Fastening splines to the panel system by mechanical means;
   b. Caulking panel joints, imperfections, overrun fasteners, cuts, and cracks with exterior grade latex caulk;
   c. Sealing the entire system with permeable latex block fill or similar primer (creating a unbroken drainage plane); and
   d. Painting the entire system with durable, exterior grade permeable finished paint.

ii. At Penetrations: (follow weather barrier details per manufacturer's instructions (discussed in Section 1.5.2 and 3.6.1.1)). This should include:

   a. Using self-adhesive flashing at all penetrations to form pan flashing, jamb flashing, and header flashing;
   b. Installing the window unit with caulk on both the face of the panel and the window frame (exterior flange windows should be used);
   c. Using self-adhesive flashing as counter-flashing to form jamb flashing and header flashing to create an unbroken drainage plane;
   d. Using a polypropylene mesh deflection and ventilation system around all flashing by stapling the product to the wall around the window penetration to form a drainage space;
   e. Installing exterior trim following the installation standards of the manufacturer for the rated wind speed and design pressure.

C. Codes and Standards:

The following codes and standards should be adhered to in the construction and testing of weather barriers:

a. <u>Weather Barrier</u> based on ASTM E331-00 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference; allow CSIPs to show conformance to 1403.2 as a weather barrier resistant to water intrusion and vapor permeance to allow drying while reducing vapor intrusion.

MANUFACTURERS should provide results and details to ASTM E331 tests. If tests are not provided, then the candidate system cannot be used as an exterior finished good, and additional *layers of finishes must be used to protect the assembly from the elements. This design document does not contemplate panels that have not successfully completed ASTM E331 tests. Note: typical CSIP details are shown and further discussed in Sections 1.5.2 and 3.6.1.1 regarding weather barrier requirements, but each vendor must show compliance as a weather barrier and may have additional information or limitations.*

b. Fiber-Cement Siding under 1405.15 Fiber-Cement Siding as a Metal Veneer assembly (requiring the same fasteners, finishes, and other performance requirements of metal veneer assemblies).

MANUFACTURERS should provide details that clearly show the facing materials fall within Fiber-Cement Siding or Fiber-Cement Paneling.

4.6 – Fire Safety

In this step, the designer will determine whether ALL relevant code issues are being met and will determine what design issues must be addressed.

4.6.1 – Fire Safety Concepts

There are two concepts that must be addressed: combustibility of the system and the system's fire rating.

A. COMBUSTIBILITY

Classification on combustible and non-combustible construction is based on the ASTM E136 - 04 Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C and ISO 1182 Non-Combustibility Test for Building Materials.

WARNING: EPS and other insulations, the core of the majority of SIP products, are by themselves combustible and have a relatively low melting point. No SIP material using polymer cores could survive 750°C and these severe tests. Therefore, SIPs are to be considered combustible construction and are limited for structural uses to Type V construction (three story max per Table 503); however, SIPs can be used as exterior wall coverings in Type I buildings per 603.1.10, "Combustible exterior wall coverings, balconies, and similar projections and bay or oriel windows in accordance to Chapter 14."

B. FIRE RATING

WARNING: Because the SIP cores are combustible, they cannot be left exposed to flame or other ignition sources and they must be protected by a thermal barrier equivalent to 15 min. exposures of gypsum (per 2603.4 Thermal Barrier). This determination relates to its fire rating or resistance to spread fire.

CSIPs have passed the ASTM E119 - 08a Standard Test Methods for Fire Tests of Building Construction and Materials to show conformance to 2603.4. Each vendor must show compliance as a thermal barrier (and weather barrier as defined in Section 4.5). All fire rating values to be used in engineering equations should always come from a manufacturer's code report (issued by a licensed, impartial third party).

4.6.2 – Validating the candidate system to the code

It is important for the designer to double check the basis of the candidate system in the code being used. This basis can be checked for validation of CSIPs, restrictions on CSIPs, and ultimately limitations on the conditions of use of CSIPs. A more detailed discussion of this is included in Section 4.2.1.

A. VALIDATION AND RESTRICTION: The basis for panels used in multistory construction are <u>validated and restricted</u> by the code, and each candidate panel system should provide evidence to show conformance to the following:
B. <u>Combustibility</u> (further discussed in Sections 1.7, 2.2.8, 3.5, and 4.2) based on ASTM E136 - 04 Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C and ISO 1182 Non-Combustibility Test for Building Materials.
    a. *MANUFACTURERS should provide results of ASTM E136-04 or EPS data showing the relative melting points of the materials used. CSIPs are limited to the following usage:*
        i. *In Type V construction (three story max per Table 503) and have limitations stipulated by the building code in Chapter 6, Types of Construction, and Chapter 5, General Building Heights and Areas. This document does not contemplate panels that are to be used in Type V construction; or*
        ii. *As exterior wall coverings in Type I buildings per 603.1.10.*

C. <u>Fire Rating (further discussed in Section 3.3.1) based on ASTM E119 - 08a Standard Test Methods for Fire Tests of Building Construction allow CSIPs to:</u>
    a. Show conformance to 2603.4 Thermal Barrier.
    b. *MANUFACTURERS should provide results of ASTM E199 tests. If tests are not provided, then the candidate system cannot be used as an interior finished good and additional layers of fire protection must be used.*
D. LIMITATIONS: The basis for panels used in multistory construction is <u>further limited</u> by the following:
    a. <u>Building Heights</u>, Table 503 (further discussed in Section 1.7) limits the floor area, heights, use, and other planning decisions based on the construction type of the building's core; and
    b. <u>Limitations to fire ratings</u>, Table 601 (further discussed in Section 2.2.8) limits the application further:
        i. CSIPs must obtain a fire separation distance greater than or equal to 30' (per Table 602) for exterior walls. Exterior coverings must be 30' from other exterior walls.
        ii. CSIP joints in exterior walls are not required to have a fire rating (per 704.13).

iii. *MANUFACTURERS have no responsibility to provide information relevant to these issues. However, DESIGNERS must understand these and other code limitations to the use of all building materials in designs. Those items listed above are not exhaustive, but are primary issues that must be addressed in preplanning activities.*

Each manufacturer should supply data (through evaluation reports) or certification reports that its system complies with the respective codes in the ICC.

4.6.3 – Specific Curtain Wall Issues

The path by which fire and smoke can spread between floors is a critical design issue. Fire-Proofing and smoke sealing the gaps between the curtain wall and the edge of the slab are essential to compartmentalize the floors. This compartmentalization between floors slows both fire spread and smoke spread.

There are two methods by which the compartmentalization can be addressed. Both methods need independent testing by the manufacturer to show conformance of the build system to the building code. The methods are:

A. Fire stop – by a minimum of ½" poured smoke seal to develop the compartmentalization, or
B. Perimeter fire containment systems that remain in place for the specified duration of the required fire rating.

These details will be developed by the manufacturer and the designer on a case-by-case basis. However, common details are shown below and throughout this guide.

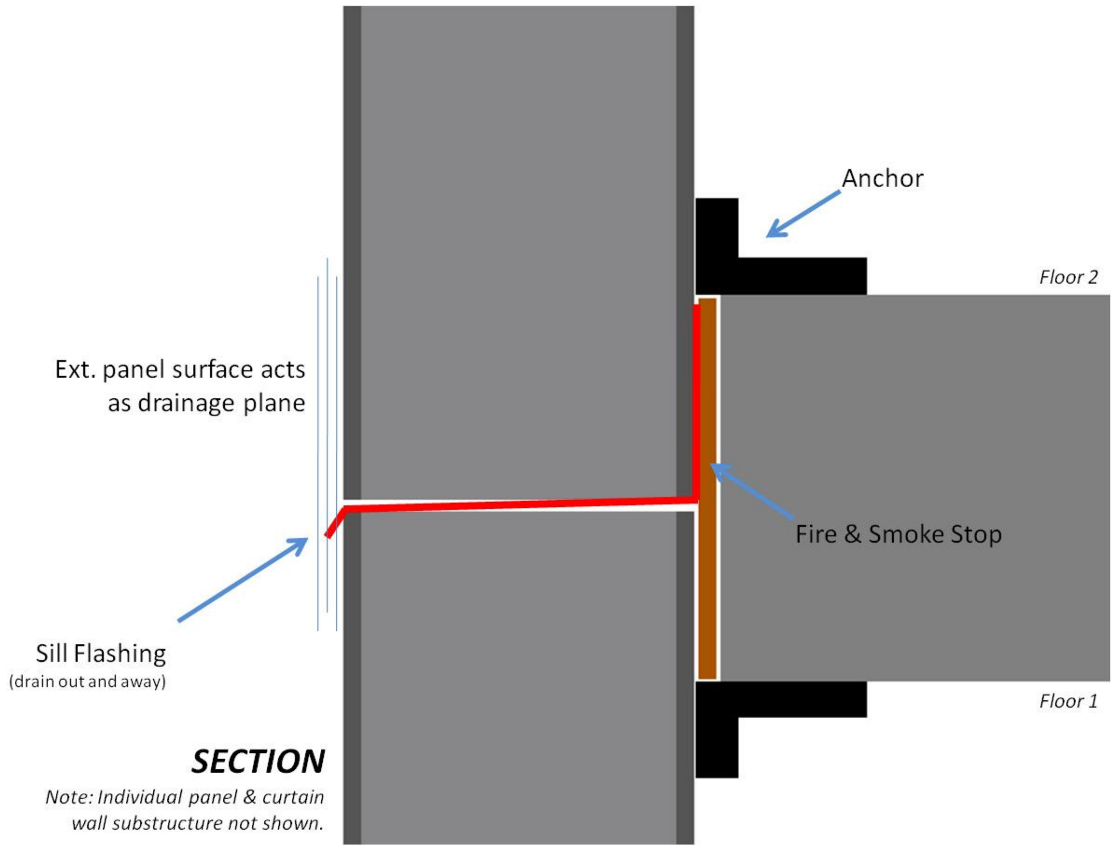

Figure 59 - Common Fire Stop Details

4.7 – Testing

Not all designs require testing. For small buildings, it is rare to specify testing as long as performance data for the application, use, and details is available from the manufacturer along with panel certifications (refer to Section 4.2.1 for more information). For larger buildings and projects, testing is required to ensure that all details and assumptions meet or exceed the performance requirements. Additionally, for large buildings, it is recommended that the systems be certified for the specific use following the details supplied. Testing of individual panels is referenced in Section 2 and testing of systems is discussed herein.

Testing of curtain wall assemblies is covered by multiple ASTM standards. Both the CSIP assembly and the whole constructed wall unit should be tested depending on the project size.

A. Testing the CSIP Assembly: typically, CSIP manufacturers have tested their systems' compliance with the following tests for the individual panels alone and panel to panel conditions.
    i. <u>Structural</u> by ASTM E72 - 05 Standard Test Methods of Conducting Strength Tests of Panels for Building Construction (referenced in Section 2.2)
    ii. <u>Weather Barrier</u> by ASTM E331-00 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference (referenced in Section 3.2)

iii. Thermal Barrier equivalent to 15 min. exposures of gypsum by ASTM E119 - 08a Standard Test Methods for Fire Tests of Building Construction and Materials (referenced in Section 3.2.2)

B. Testing whole wall assemblies as units: manufacturers do not have standards yet for curtain wall assemblies, and if manufacturers have this data, the specific designs may be modified by the architects, which would invalidate the test. For these reasons, large-scale projects require the following tests:

  i. Structural determination as well as the failure mode at ultimate by ASTM E330 - 02 Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference; however, there is frequently no need to verify the structural performance of a system by physical testing if the wall is of a conventional, simple, or a straightforward design. Engineering analysis can often determine the safety and adequacy of the design.

     WARNING: However, because CSIPs have not yet been used as curtain walls, it is recommended that the industry work together to validate the design document to develop a consensus within the industry and validate that consensus through independent testing following ASTM E330 – 02.

  ii. Air leakage by ASTM E283 - 04 Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen

  iv. Weather Barrier by the following:

     i. ASTM E331-00 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference,

     iv. ASTM E547 - 00 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference, and

     v. AAMA 501-4 Dynamic Rain Penetration Test (may be required).

  iii. Thermal Barrier equivalent to 15 min. exposures of gypsum by ASTM E119 - 08a Standard Test Methods for Fire Tests of Building Construction and Materials (referenced in Section 3.2.2) may be required for the whole assembly, or may simply use the thermal barrier results from the individual panel assembly. This will ultimately be determined by the specific project usage of panels.

4.8 – Achieving LEED Certification

While not necessary to design procedures, building owners and designers often want to certify their building as "green." The U.S. Green Building Council has built a strong brand as the leading organization for this certification. To achieve the USGBC's LEED certification, the project's design, construction, and building commissioning must be documented and submitted to the USGBC for review. The LEED rating system awards points for meeting different energy and environmental criteria in areas such as building site, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and more. Points for the entire project are summed, and the project total falls into a tiered certification category (certified, silver, gold, and platinum certification).

For multistory construction, the LEED for New Construction (LEED-NC) checklist is the most applicable. Unlike other LEED checklists, SIPs are not called out directly for new construction projects. However, the indirect gains add up quickly. Of the sixty-nine potential points on the LEED-NC scale, twenty-six points are required to be certified, thirty-three for silver, thirty-nine for gold, and fifty-two for LEED platinum.

- Up to ten points are possible for optimizing energy performance, based on a percentage improvement in the building performance rating compared to the baseline performance rating per ASHRAE/IESNA Standard 90.1-2004. While SIPs are not the only factor in a building's energy performance, they have been shown to improve energy efficiency by 35 to 50% compared to stick-built construction, making them a significant step toward these ten possible points.
- Two points can be awarded if a project diverts 75% of material from disposal during construction. SIPs are fabricated to be the exact size necessary for a building project, and with walls and roofing making up a considerable percentage of a project's total construction material, using SIPs is a significant step toward the total of 75%.
- Two points can be earned if more than 20% of the project's building materials are manufactured within five hundred miles of the site. While the percentage of a project's total material depends upon the specific design, SIPs account for a large amount of a building as the entire building envelope. With SIP manufacturing facilities located throughout the country, using locally produced SIPs makes earning these two points relatively easy.
- Up to two points in innovative design for exceptional performance and as an innovative material.

These potential points add up to a total of sixteen. While it is not as simple meeting the minimum point value (there are several prerequisites for certification), using SIPs in a new construction project can indirectly contribute to as much as 60% of total points needed for LEED Certification or 30% needed for LEED Platinum certification.

Achieving this rating requires following the USGBC's LEED for New Construction certification process, which requires documentation of the design, construction, and building commissioning. More specific information can be obtained from the USGBC.

4.9 – Summary

- In designing for sustainability and structural performance, the following major characteristics of CSIPs can be leveraged:
    - Thermal performance
    - Construction time
    - Increased comfort
    - Decreased job site waste
- Three methods exist for CSIP candidate selection:
    - Using code-recognized systems
    - Using a certified, listed, or evaluated panel system
    - Using an uncertified system
- Elements of CSIP integration as a curtain wall
    - Anchor to frame details, mainly structural, which allow movement
    - Structural specifications for intermediate frame
    - Panel system type
    - Window unit type
    - Exterior trim type
    - Construction of the totality of the unit system assembly
- Structural
    - Analysis of panel properties
    - Analysis of panels as a system
    - Analysis of substructure to the building frame
- Optimizing the thermal envelope
    - Temperature-driven heat transfer
    - Infiltration
- The following areas must be optimized:
    - Baseline panel (CSIP thickness)
    - Substructure joints (CSIP to unit boundaries and unit to unit connections)
    - Spline joints (CSIP to CSIP connections)
    - Penetration joints (CSIP to penetrating unit connections)
- Specific control measures
    - Moisture and condensation control
    - Rain penetration control
    - Codes and standards
- Fire Safety
    - Combustibility
    - Fire rating
    - Validating the candidate system to the code

5 – Conclusions

5.1 – General Conclusions

SIPs are characterized by their composite nature, which makes them versatile and desirable for both single- and multistory construction. For both building types, CSIPs are an enabling technology that reduces substructure demands. CSIPs also offer an easily constructed, thermally efficient, cost-effective alternative building envelope. The wealth of materials and design options available in the SIP industry allows considerable flexibility for new SIP designs and uses. All of these performance advantages have been discussed herein.

This report can serve as a decision resource for future work on the use of CSIPs in multistory buildings and as a road map for CSIP manufacturers to engage commercial construction. This project has systematically compiled the information necessary for manufacturers to make an informed decision to develop systems and for engineers to work with manufacturers to apply those systems to multistory construction. It completes the work necessary to provide all information, data, and recommendations needed to support decisions about future work on the use of CSIPs in multistory buildings without basing any conclusion or recommendation on proprietary systems, properties, or connections. This report also details the procedure to be used for the final design of, and for obtaining building officials' approval of, construction of multistory buildings using CSIPs as curtain walls and discusses the limitations and restrictions placed on the systems. It should be sufficient in detail to allow a knowledgeable engineer to replicate the design process.

CSIPs require significant development to fully embrace their potential. This research serves as a benchmark evaluation of the potential applications and future development of the CSIP industry. It is now the manufacturers' challenge to work as an industry and continue the work this document began. This involves implementing the design procedures discussed herein and obtaining appropriate evaluation and agreement as an industry that the design procedures are suitable for adoption and use in building design and construction practice.

As a result, this document serves as a benchmark for improvement in the industry and to demonstrate the CSIP potential for multistory construction, leveraging the properties of the panels and the systems advantages as factory-manufactured assemblies.

5.2 – Dissemination Plan

The keystone to the success of this research document lies with communicating the findings of the research to the proper industry personnel. Without properly achieving this goal, the potential impact of the project will not be fully realized. FAS will disseminate results of the proposed research primarily to niche construction markets to enable practitioners to easily access and use the information. FAS plans on taking a varied approach to this task, approaching professionals in all areas of the building industry through a variety of media. Steps planned include the following:

- FAS will publish the full text of the final report on the FAS website for easy and ready access by any interested party. FAS will publish paper copies for distribution as well.

- FAS will coordinate with the Pankow Foundation and our collaborators to make spokespersons available for press interviews. The FAS outreach campaign will focus on generating news coverage of research.

- FAS will present the findings of the research at conferences for niche construction audiences. FAS's Brian Doherty chaired a presentation on FAS's work at the American Society of Civil Engineers Architectural Engineering Instutitute Conference in September 2008.

- FAS will contact peer-reviewed journals to publish relevant articles. FAS will target periodicals that serve a niche construction market and has identified the following as potential publication journals:

    Automated Builder; *Concrete Concepts*; *Building Design and Construction*; *Concrete Construction*; *Journal of Building Enclosure Design*; *Building Systems Magazine*; *Means, Methods, and Trends*; *Journal of Composites for Construction*; *Journal of Materials in Civil Engineering*; *Practice Periodical on Structural Design and Construction*; *Journal of Architectural Engineering*; *Electronic Journal of Structural Engineering*; *Journal of Green Building*; and *California Builder*.

- FAS will contact organizations that cater to builders and building owners to publicize the final report among related groups. These include:

    Fannie Mae, the Joint Center for Housing Studies at Harvard University; the National Association of Home Builders, as well as the Department of Housing and Urban Development and the Department of Energy.

- FAS will work with the Architectural Engineering Institute of the American Society of Civil Engineers to benefit from its contacts and expertise to target the desired audience and better disseminate research results.

5.3 – Future Research

This research project has identified several outstanding issues and qualifications the industry needs to address. These include:

1. The definition of a SIP is vast and various. There is no industry-specific definition of SIPs; therefore, all sandwich panels fall within this general category, no matter if they are laminated, reinforced, or hybrids of traditional systems (i.e., including intermediate supports). The testing standards should recognize and address this deficiency and specify composites that fall within the definition of a SIP. These testing standards should also address limitations and reinforcements.
2. Openings and penetrations are not properly addressed within the analysis of SIPs. The testing standards should address penetrations in the wall by setting ranges of unsupported penetration spans.
3. Connections throughout the industry have been driven by constructability issues and not engineering analysis and optimization. Sufficient research needs to be directed into the research of new connection systems, evaluation of connections, and generally accepted connection standards. Connections will be the limiting factor of shear and combined loading, which may benefit the structural performance of buildings.
4. Diaphragm assemblies need more thorough testing in the industry. Combined shear and tension acting on the panels is assumed to be carried at the connection. The testing standards should include some acknowledgement of diaphragm testing procedures and creep.
5. Knowledge of adhesives and long-term durability must be evaluated against the durability of the subsequent constituent materials. Are the adhesives perfectly rigid like the facing materials to only be attached to a flexible core, or are the adhesives flexible? Is the durability of the system limited to the lowest durability of the constituent materials?
6. Fire resistance needs more education within in the industry. SIPs may be fire-rated, but they are not non-combustible. The fire resistance of a polystyrene core is always going to be the limiting factor, thus new insulations must be deployed if SIPs are to ever be considered for uses in bearing wall construction of multistory buildings. The SIP industry needs more education of architects and engineers on the fire-resistance aspects of the products for them to be accepted for non-residential uses.
7. The industry needs standards for manufacturing, testing, material handling (including maintaining the chain of custody and compliance) and industry-accepted quality assurance and control.

List of Abbreviations

- American National Standards Institute (ANSI)
- Cementitious Structural Insulated Panels (CSIP)
- Computer-aided Design (CAD)
- Computer-aided Manufacturing (CAM)
- Department of Energy (DOE)
- DOE's Building America (BA)
- Engineered Wood Association (APA)
- Environmental Protection Agency (EPA)
- EPA's Energy Star (ES)
- Expanded Polystyrene (EPS)
- Expanded polystyrene (EPS)
- Extruded polystyrene (XPS)
- Housing and Urban Development (HUD)
- HUD's Partnerships for Advanced Housing Technology (PATH)
- ICC's International Building Code (IBC)
- ICC's International Energy Conservation Code (IECC)
- ICC's International Residential Code (IRC)
- International Code Council (ICC)
- Leadership in Energy and Environmental Design (LEED)
- National Institute of Building Science (NIBS)
- NIBS's Whole Building Design Guide (WBDG)
- Oriented Strand Board (OSB)
- Poly-urethane (PU)
- Return on Investment (ROI)
- Structural Insulated Panel Association (SIPA)
- Structural Insulated Panels (SIP)
- USGBC (US Green Building Council)
- USGBC's LEED for New Construction (LEED-NC)

List of Definitions

Materials and Manufacturing Related

- Adhesive Viscosity: the adhesives resistance to flow (resistance to being deformed by shear and tensional stresses as a liquid). Adhesives with low viscosities flow freely and those of high viscosities have a resistance to flow. The measurement of adhesive's fluid friction.
- Bonding Pressure: Pressure applied or exerted at the time of bonding two elements or materials together.
- Core Materials: Those materials forming the core of a sandwich panel.
- Facing Materials: Those materials forming the faces of a sandwich panel (or the outer layers)
- Sandwich Panel: A class of composite materials formed by assembling two thin stiff skins (Facing Materials) to a lightweight, thick core (Core Material)
- Curing Shrinkage: Dimensional shrinkage or contraction due to the curing of subcomponents or materials used to combine two or more elements or materials together.
- Fiber-cement board: a planar sheet of concrete composed of concrete, sand, fillers, and fibers to increase ductility and decrease damage. Most fiber cement boards are manufactured using the Hatcheck method.
- Hatcheck method or Hatcheck process: a manufacturing method for thin concrete sheets using extrusion, molding, and placement of fibers in layers to form large planar sheets.
- Viscoelastic Properties: the properties of a material to exhibit both viscous and elastic properties. Viscous materials resist shear and strain when applied. See also, Adhesive Viscosity as it applies to making sandwich panels in joining the facing and core materials.
- Core Indentation: Any marks, indentations, and defects in the core material.

Code Related

- Air Barrier: air barriers control air leakage into and out of buildings through the building envelope given a low air permeance. They keep moisture laden air from transferring between the building envelopes. Air barriers consist of mechanically attached membranes (such as housewraps), self adhered membranes, fluid applied membranes, closed cell spray applied foams, and open cell spray applied foams.
- ANSI process: the process regulated by ANSI to develop standards in a fair and equitable manner.
- Combustibility: combustibility is the measure of how easy a substance will burn through fire or combustions. Combustibility can be measured through testing.
- Importance Factor: The importance factor for wind (and snow) load design is used to calibrate the recurrence interval above and/or below the normal design condition.
- Life-safety Performance: the performance conditions and parameters that protect an occupant's life and safety in a building and are imposed to reduce risk to the building occupants, owners, and users.
- Multistory: buildings with more than three stories which is the current limitation for SIP construction per the IRC and IBC code.

- Prescriptive Method: Prescriptive methods are those methods and requirements which are prescribed, or set down as rule or guide, in a code. Prescriptive methods, as such, are very narrow in focus and offer little substitution.
- Sustainable Performance: the performance conditions and parameters that relate to the environmental sustainability or measures of a component, assembly, product, or building. Common metrics are USGBC's LEED program.
- Vapor Retarder or Vapor Barrier: vapor barriers are semi-impermeable barriers that resist the diffusion of moisture through a building envelope. They are engineered with varying degrees of permeability (between 0.1 – 1.0 perm).
- Water-resistive Barrier: water resistive barriers are impermeable/impervious barriers that resist the diffusion of any moisture through a building envelope. They are engineered with zero permeability (0.0 perm).

Construction Related

- Capillary Break: a space between two surfaces or elements which is wide enough to prevent the movement of moisture through the space by capillary action.
- Chase: a engineered space which is designed to run services, mechanical equipment, and other ancillary functions necessary to meet code or other performance requirements.
- Head Flashing: the horizontal flashing installed over a window opening or other penetration through the building envelope to control or prevent moisture migration through the assembly.
- Jamb Flashing: the vertical flashing installed in a window opening or other penetration through the building envelope to control or prevent moisture migration through the assembly.
- Pan Flashing: the horizontal flashing installed under a window opening or other penetration through the building envelope to control or prevent moisture migration through the assembly.

Engineering Mechanics Related

- Area Moment of Inertia or the Second Moment of Area: a property of a shape that can be used to engineer the resistance of beams to bending and deflection.
- Bending Moment: the moment applied to an element so that it bends inducing tensile and compressive stresses.
- Buckling: a failure mode due to high compressive stresses (causing deformation of buckling before failure).
- Composite: any material in which two or more distinct materials are combined together, yet remain uniquely identifiable in the mix
- Deformations: a change in the shape or size of an object due to an applied force
- Ductile: a mechanical property used to describe the extent to which materials can be deformed plastically without fracture.
- Young Modulus or Modulus of Elasticity or Elastic Modulus: a measure of the stiffness of an isotropic elastic material defined as the the ratio of the stress over the strain (in the range of stress in which Hooke's Law governs).
- Fatigue: failure caused by repeated stress in materials.
- Fracture Strain: strain developed in brittle materials which can lead to fracturing, decrease strength, or failure.

- Modes of Failure: structural failure cases for mechanical failure including impact, fatigue, creep, rupture, stress concentrations, etc.
- Mohr's Circle: a two-dimensional graphical representation of the state of stress at a point.
- Moment of Inertia or Mass Moment of Inertia: a measure of an object's resistance to changes in the rate of rotation or the inertia of a rigid rotating body with respect to the rotation.
- Neutral Axis: Axis in the cross section of a beam which there are no longitudinal stresses or strains.
- Normal Stress: stress applied perpendicular to a face of a material.
- Saint-Venant's Principle: "... the strains that can be produced in a body by the application, to a small part of its surface, of a system of forces statically equivalent to zero force and zero couple, are of negligible magnitude at distances which are large compared with the linear dimensions of the part" (*Augustus Edward Hough Love)*
- Shear Failure: Failure of a material due to shear forces.
- Shear Stress: Stress applied parallel to a face of a material.
- Stiffness-to-Weight Optimization: Optimization concept of a sandwich panels stiffness in regards to its weight. Stiffness to weight optimization will yield the most cost effective structure.
- Thermal Stress: resultant stresses in an element or member due to applied thermal energy.
- Wrinkling: the failure of sandwich panels where the facing materials wrinkle or buckle due to compressive forces in the (face) of the sandwich panel.

Mechanical Loading Related

- Axial Loading: Loading of a panel so that its axial strength is taken advantage of or tested.
- Compressive Strength or Compressive Resistance: a material's resistance to compression stresses when loaded.
- Compressometers: device used to measure compression in a structural member.
- Deflectometers: device used to measure deflection in a structural member.
- Diaphragm: a structural system used to transfer lateral loads to shear walls or frames through in-plane shear stress. Flexible diaphragms resist lateral forces depending on the tributary area irrespective of the member's flexibility; rigid diaphragms transfer forces to frames or shear walls depending on the member's flexibility and location in the structure.
- Flexural Rigidity: the required force couple (a system of forces with a resultant moment but no resultant force) required to bend a rigid structure into a curved structure.
- Flexural Strength or Bending Strength or Flexural Resistance or Bending Resistance: a material's resistance to bending stress when loaded.
- Impact Strength or Impact Resistance: a material's resistance to impact loads and objects.
- Racking Resistance or Shear Resistance: a material's resistance to racking or shear stresses when loaded.
- Tensile Strength or Tensile Resistance: a material's resistance to tensile deformation (necking) when loaded.
- Transverse Loading: Loading of a panel so that its transverse strength is taken advantage of or tested.

Curtain Wall Systems

- Column-cover-spandrel System: curtain wall system that is a hybrid between panel systems and spandrel panel systems which allow panel units to act as spandrels tying columns and floor/roof planes together for additional support and rigidity. These systems are not typical.
- Independent Unit Systems: curtain wall system where the individual units are independent of each other, are free to move/translate/expand, and are self sealing to air infiltration and moisture migration.
- Infill Panels: sandwich panels which are used to build larger pieces and components of unit, unit mullion, and panel systems.
- Infill Window Units: window units which are used to build larger pieces and components of unit, unit mullion, and panel systems.
- Panel System: curtain wall system comprised of large monolithic panels (typically pre-cast concrete).
- Spandrel Panel: the vertical end wall panel typical of concrete construction that ties a horizontal floor/roof planes to the columns for additional support and rigidity.
- Sticks System: curtain wall system comprised of individual pieces built piece by piece.
- Units System: curtain wall system comprised of larger units built from small pieces. Unit systems are cost effective, leveraging off site assembly and rapid on site construction.
- Units-mullions System: curtain wall system that is a hybrid between unit curtain wall systems and stick curtain wall systems that use sticks and mullions to hide and held control water infiltration through the installed unit systems.

Heat Transfer Related

- Blower Door: A blower door is a test for building air tightness that consists of a fan that mounts into the frame of an exterior door which depressurizes the house. A calibrated blower door can calculate the whole building tightness and the natural air exchanges in the house.
- Conduction: the transfer of thermal energy between two elements (through the vibrations at a molecular level through a solid/fluid).
- Convection: the transfer of thermal energy through bulk motion of fluids.
- Infiltration: the introduction or passage of air into a building through cracks, windows, joints, or other known/unknown penetrations. Infiltration is also known as air leakage.
- Radiation: the transfer of thermal energy through electromagnetic waves.
- R-factor or R-value: the measurement of thermal resistance of an insulation product. The R-value of the material is the material's thermal resistance coefficient. The larger the R-value the better the material is as an insulator. $R = 1/U$
- Thermal Bridging or Thermal Shorts: A condition when materials come in contact and create a heat flow or transfer path. Thermal bridges decrease the thermal performance of an assembly.
- Thermal Breaks: A condition when materials are broken therefore creating a broken heat flow or transfer path. Thermal breaks increase the thermal performance of an assembly.
- U-factor or U-value: the measurement of heat transfer through a material. The U-value of the material is the material's heat transfer coefficient. The larger the U-value the worse the material is as an insulator. $U = 1/R$

- Whole-wall R-value: Whole wall R-value is the summation of the whole wall's R-values and not the R-value of an individual section of the wall.

Splines

- Spline: A spline is a mechanical member that connects two panels in-plane by mechanically fastening the facing components together to keep the faces parallel.
- Full Spline: A spline that connects the panels by one solid member. (Refer below for a diagram and relative performance)
- Guarded Offset Spline: A spline that consists of a large member (often designed for structural reasons) separated by a thermal break and a smaller member which combined mechanically fastening the facing components together to keep the faces parallel. (Refer below for a diagram and relative performance)
- Guarded Spline: A spline that allows for the mechanically fastening the facing components together to keep the faces parallel but is thermally broken from the facing materials by being centered into the core material. (Refer below for a diagram and relative performance)
- Offset Spline: A spline that consists of a large member (often designed for structural reasons) that attaches to only one facing of the panel and is separated by a thermal break from the remaining face. (Refer below for a diagram and relative performance)
- Surface Spline: The most common spline type in SIP construction. Surface splines consist of mechanical connection only between the facing materials and have engineered thermal breaks consistent with the core material.

Typological Connection Type & Relative Performance

	U-factor	R-factor	Error
Blank panel (baseline) *Assumed baseline panel*	0.0400	25.00	0.00%
Wood Surface Spline	0.0416	24.04	1.70%
Metal Surface Spline *Preferred panel to panel connection.*	0.0430	23.26	4.50%
Full Wood Spline	0.0580	17.24	1.20%
Full Metal Spline	0.1752	5.71	7.95%
Guarded Metal Tube	0.0862	11.60	6.53%
Guarded Metal Solid *Preferred substructure panel connection.*	0.0870	11.49	6.56%
Metal Offset Spline	0.1154	8.67	7.61%
Guarded Metal Offset Spline *Preferred substructure panel connection.*	0.0709	14.10	8.99%

Note: assume 5.5" insulation core throughout.

Referenced Appendices

A. Current SIP Prescriptive Method for the International Residential Code
B. Seismic Research Report
C. FAS Report on Certification Options
D. Wind Research Test Report
E. Draft SIP ANSI Standard