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# Structural Insulated Panels (SIPs) in Construction; Energy Efficiency, Seismic Performance and Sustainability: A Review

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***Abstract*** **–** The construction industry faces significant challenges related to energy dependency, outdated technologies and slow adoption of energy saving measures. In response, there has been a surge in technological advancements including the development of structural insulated panels (SIPs). Structural insulated panels (SIPs) are gaining popularity in the construction industry as an innovative solution to address energy conservation, environmental concerns and lifecycle costs. SIPs consist of a foam plastic insulation core sandwiched between two structural panel facings, offering superior insulation properties, airtightness, improved thermal comfort, lower lifecycle costs and ability to reduce energy consumption which contribute to overall energy savings. The use of SIPs addresses the global challenge of energy conservation in buildings which consume over 85% of energy resources. Additionally, SIPs provide enhanced seismic performance due to their stiffness and specially designed connections making them effective in resisting lateral forces during seismic events. As energy prices rise and global carbon dioxide emissions remain a concern, the market for SIPs is expected to grow, driven by their ability to meet stringent building regulations and contribute to the construction of energy efficient buildings. The adoption of SIPs in the construction industry presents significant opportunities for sustainable and energy efficient buildings contributing to the reduction of global carbon dioxide emissions and promoting occupant well-being in the face of rising global temperatures and urban heat effects.

*Keywords – Structural Insulated Panels (SIPs), Energy Efficiency, Seismic Performance, Carbon Dioxide Emissions and Lifecycle Cost.*

## I. INTRODUCTION

The world faces a significant energy dependency challenge across all sectors with particular emphasis on energy conservation in construction and urban areas which consume over 85% of energy resources. This stems from an imbalanced energy consumption structure, outdated utility technologies, slow adoption of energy-saving measures and insufficient building modernization efforts [1]. Technological advancements have influenced every aspect of our lives including the construction sector where traditional methods still dominate despite the push for prefabrication technology to address environmental concerns and reduce lifecycle costs [2]. Over the years, many new construction methods have emerged with one of the latest innovations being the development of structural insulated panels (SIPs). This is a new strategy that is being employed to reduce the construction time and also improve the energy conservation properties of a building. Structural insulated panels (SIPs) are quickly gaining popularity in the construction sector. They consist of a foam plastic insulation core sandwiched between two structural panel facings like oriented strand board (OSB) or plywood as shown in Figure 1 [3]. The use of these panels as a method of construction has started increasing and it has been estimated that it will take over the market of traditional frame construction very soon. However, the introduction and the application of these technologies can be regarded as one of the most vital changes in the history of the construction, the energy conservation and environmental friendly buildings [4]. Structural insulated panels (SIPs) are a high-performance building system used in both residential and commercial construction. This type of panel is very light yet strong enough to carry heavy loads, it combines three functions into one building system: the structure, the insulation and the internal vapor barrier, it can be used for all building applications i.e. walls, pitched roofs, flat roofs and floors. SIPs are produced under adverse factory conditions and can be manufactured to fit a specific design. The result is a high-performance, energy efficient and cost-effective panel that replaces more conventional construction methods [5]. This type of system also offers a high-quality internal environment in terms of air tightness, sound and thermal insulation. Some additional benefits of using SIPs in the building envelope include potential cost savings through reduced air handling equipment, greater flexibility in architectural design and assembly, shorter construction time, improved on-site productivity (particularly in adverse weather conditions) and their lightweight nature puts less heavy foundation requirements on the building potentially providing cost savings [6].

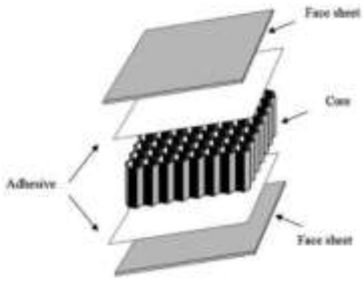


Figure 1. Design Concept of SIPs [16]

As energy prices rise over time, there is a growing preference for SIPs due to their high insulation levels meeting the demands of building regulations. The market for SIPs is expected to grow and become more stable; the SIPs industry is still at its early stage compared to the long history of traditional materials [7]. New technologies have been developed to improve fabrication and application methods and to address the fire performance and structural robustness of the panels [8]. The SIP technology has brought a lot of opportunities in the construction industry. It is essential for everyone in the industry to understand and effectively use this technology [9]. Studies have shown that buildings consume about 40% of the total energy used in the world and produce 37% of global carbon dioxide emissions. SIPs make buildings consume less energy which reduce the energy cost [10]. Buildings with SIPs provide improved thermal comfort and benefiting well-being of the occupants particularly in the face of rising global temperatures and urban heat effects. These energy efficiency advantages can lead to lower life cycle costs for property owners and contribute to overall energy savings for the country [11]. Structural insulated panels (SIPs) provide superior insulation compared to traditional wood framing because of their solid insulation core and controlled fabrication environment. SIPs ensure airtightness, eliminating the need for additional measures like double layers of plasterboard or external insulation which can alter the appearance of building. In addition, SIPs address thermal bridging issues by combining structural and insulating elements into one material. Typically using polystyrene insulation, SIPs promote optimal thermal comfort by preventing heat loss and reducing cold spots and drafts, thereby enhancing the overall thermal performance of a building

[12]. Structural insulated panels (SIPs) achieve their superior air tightness through high-density polyurethane (PUR) insulation, ensuring long-term R-value. Unlike traditional timber frame walls requiring two separate insulation materials, SIPs use continuous PUR eliminating gaps and improving R-value. SIPs, combined with mechanical ventilation systems enhance energy efficiency and indoor air quality reducing maintenance costs. SIP construction promotes fast assembly, accurate engineering, meets zero carbon targets and reducing onsite errors and waste. Using SIPs eliminates air leakage risks, supports exceptional energy efficiency and prepares buildings for future energy demands [13]. ASCE-7, the American Society of Civil Engineers standard guides seismic risk assessment in the building sector. Seismic resistance relies on both loads and component stiffness, ASCE 7-10 underscores the importance of material choice and arrangement. Structural insulated panels (SIPs) known for their stiffness and specially designed connections are effective in resisting lateral forces during seismic events. SIPs seismic performance has been endorsed by the Structural Insulated Panel Association (SIPA), with ongoing research and real-life projects demonstrating their effectiveness in seismic zones [14]. Structural insulated panels (SIPs) offer exceptional strength and stability distributing seismic forces throughout the building and enhancing overall safety. By leveraging SIPs rigidity and advanced engineering simulations, structural stability can be optimized even before construction begins showcasing a progressive approach to seismic design in the construction industry. This not only ensures durability and resilience against seismic activity but also highlights the potential of SIPs to revolutionize construction practices [15]. Incorporating insulation materials and advanced structural design enhances ability of the building to withstand seismic events making structural insulated panels (SIPs) a valuable asset in modern construction for energy efficiency and resilience.

## II. Design Formulations for SIPs

After World War II, there was a high demand for residential housing construction across the United States. To meet this demand quickly and affordably, builders simplified existing techniques and adopted alternative methods. One such method was the evolution of sandwich panels. Originally developed in the 1930s and 1940s for military housing and commercial use sandwich panels combined steel and foam to create temperature-controlled spaces as shown in Figure 2. In the 1950s, this approach was applied to residential housing using corrugated hardboard sheathing, expanded polystyrene (EPS) foam insulation and polyurethane insulation. While technically similar to modern SIPs, this early version was less refined and standardized.

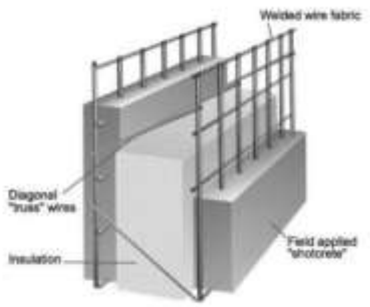


Figure 2. Concrete Polystyrene SIPs [17]

The first structural insulated panel was created in 1935 at the Forest Products Laboratory in Madison Wisconsin, USA. It consisted of a press that held two to four inches boards together while being injected with a urea formaldehyde adhesive. While early SIPs with insulation board between two structural skins date back to the 1930s, the modern version emerged around 1952 in Sweden and gained popularity in the US during the 1970s energy crisis. This development involved using expanded polystyrene insulation laminated between two OSB boards with adhesive, a method still widely used today. Initially fabricated on-site, the concept of pre- fabrication quickly gained traction with panels being pre-cut to specific dimensions in factories and then shipped for easy assembly, a practice that became common in the 1980s. A more recent innovation in SIP production is the development of insulating concrete formwork (ICF) or SIPcrete as shown in Figure 3.

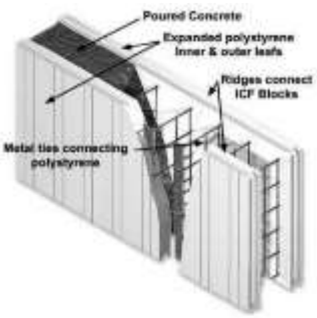


Figure 3. Insulating Concrete Formwork (ICF) or SIPcrete [18]

This method needs constructing a frame using interlocking hollow extruded polystyrene blocks which are then filled with concrete. This results in a structure with exceptional impact resistance and compressive strength developed in response to height concerns about building in areas prone to natural disasters or severe weather conditions. Additionally, it is worth noting that there are SIPs made from materials other than OSB and expanded polystyrene representing the latest advancement in SIPs manufacturing. These alternative SIPs may utilize various materials for the skins and insulation including metals, different plastics and foams. For instance, an alternative SIP could consist of two skins made of fiber-reinforced plastic with a polyurethane foam core. Between 1935 and 1970, early SIP development mainly focused on using fiberglass insulation sandwiched between hardboard sheets. However, these panels faced issues such as high susceptibility to moisture, low strength and difficulty in creating tightly sealed building envelopes. In the mid-1970s, laminators made various changes to enhance panel strength including using thermal-setting resins vertically applying load-carrying members to reduce material costs and gradually incorporating oriented strand board (OSB) or plywood. The shift towards OSB marked a significant advancement in SIP development due to its cost-effectiveness, consistency, superior dimensional stability and higher internal strength compared to plywood. Additionally, the introduction of a polyurethane foam core during this period led to SIPs with improved insulation value, rigidity and ease of handling. Since the late 1970s, SIP advancements have focused on increasing cost efficiency and marketability by enlarging panel sizes, enhancing joining systems and refining handling and transportation methods. Today, modern SIPs closely resemble those developed in the late 1970s, featuring an OSB or plywood skin bonded to a foam plastic core. By the 2000s, government funding for energy efficient projects like the green and more energy efficient homes Initiative, sponsored by the Department of Trade and Industry (DTI) led to increased research and adoption of SIP technologies in new housing construction with funding continuing until 2007. Today, SIPs have evolved from their early versions to meet the challenges and demands. Modern core materials such as polyurethane (PUR) and expanded polystyrene (EPS) have replaced older types like mineral wool and phenolic foam due to their superior insulation properties. Magnesium oxide (MgO) particle board is gaining attention for its excellent fire resistance and weatherproof characteristics. Oriented strand board (OSB) has become the standardized facing material to maximize structural performance. While magnesium is emerging as an alternative, current safety and health regulations favor OSB due to its long-term stability. SIPs are not only used in the building industry but also in aeronautical and marine applications, such as cabin construction in aircraft and ship compartments, due to their outstanding fire retardant and lightweight properties. Further development in SIP technologies aims to enable the creation of heavier and larger building components like floor and roof panels, minimizing construction time. Despite limitations, SIPs are increasingly accepted as an alternative energy-efficient construction method in the building industry. Now, SIPs are commonly used in residential construction, including single- family homes, townhouses, and apartments. They are typically used in walls and roofs, providing structure, insulation, and sheathing all in one piece. This construction method is called "sandwich panel" construction. In roofs, SIPs rest on the outside walls, allowing for continuous insulation and air sealing. The energy efficiency of SIP-built homes is persuading more builders to use them. Typical SIPs (structural insulated panels) consist of two outer layers and an insulating inner core as shown in Figure 4. They are available in various thicknesses, with two rigid outer layers and a thicker core layer. Insulation is a crucial component of SIPs, enhancing the energy efficiency of buildings by preventing heat exchange with the external environment. The ideal insulation material should meet geographical demands economically and environmentally. Common core materials used in SIPs include expanded polystyrene (EPS), extruded polystyrene (XPS), polyisocyanurate (PIR), polyurethane (PUR) and mineral wool. Polyurethane (PUR) foam has better fire resistance and produces less smoke. SIPs made from PUR are stronger than those made from EPS or XPS for axial, flexural and lateral loads. PUR also provides excellent insulation against moisture and adheres well to the outer skins. The outer layers are usually flexible skins attached to one or both sides of the core using glue bonding, pressing or by pouring and injecting liquid foam. SIPs can have various skin materials depending on their benefits and uses such as oriented strand boards (OSB), plywood, metal, fiber cement, cement calcium silicate and gypsum. The skins must be fire-treated to meet local and national building codes.

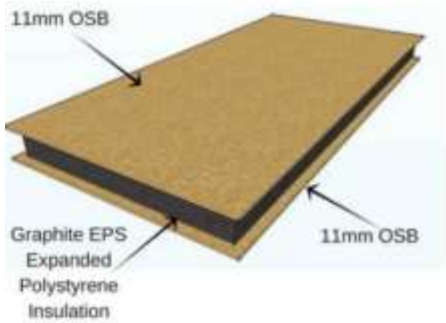


Figure 4. OSB Faced SIPs [19]

III. ADVANTAGES AND PERFORMANCE OF SIPS IN CONSTRUCTION

Structural insulated panels (SIPs) offer significant advantages in residential construction particularly in energy efficiency. The insulated foam core of SIPs minimizes heat transfer resulting in excellent thermal performance and reduced heat loss. Unlike traditional wall construction with timber studs that create thermal bridges, SIPs construction eliminates or reduces these bridges further enhancing energy efficiency. This is crucial given that a large portion of carbon dioxide emissions stem from building energy usage. SIPs high thermal performance allows for thinner walls compared to traditional methods, maximizing usable floor space. This not only reduces carbon emissions but also saves homeowners money on energy bills. The ability to easily integrate high levels of insulation and eliminate cold bridging makes SIPs an attractive choice for meeting strict energy and carbon standards in future home construction. Building a house with SIPs can be completed up to 10 times faster than stick-built homes. In contrast to traditional methods, SIPs construction eliminates the need to wait for concrete walls or studs to dry and separates the insulation process from the wall assembly. This saves time and money on insulation purchases, handling and installation. With SIPs, entire walls and roofs can be installed in just one day making it particularly beneficial in regions with harsh winter conditions. While installing structural insulated panels (SIPs) may initially cost more than traditional wooden framing, there are long-term savings and benefits that make up for this initial expense. According to a study by the SIPA Building Excellence Research Centre, SIPs offer a 22% cost saving over a 17-year lifespan of building compared to timber framing. This is because SIPs have minimal environmental impact, improve energy performance significantly and reduce labor costs over time. The main advantages contributing to these savings are the enhanced energy efficiency, structural strength of SIPs and their easier, faster and more affordable construction and maintenance. SIPs have excellent sound insulation properties. Typically made of oriented strand board (OSB) and rigid foam insulation, SIPs effectively block sound transmission. The continuous foam and double stud framing technique used in SIP installation minimize sound transmission through the panels. In a study, SIPs were found to reduce sound pressure levels between the exterior and interior of a house by 28.7 to 39.5 decibels, outperforming typical wall systems by 15 to 19 decibels. This superior sound insulation is due to SIPs scattering sound waves and reducing the energy that can travel through the panel preventing sound from passing through walls. This creates a peaceful living environment especially beneficial in noisy areas or densely populated regions. Additionally, incorporating anti- vibrational sound-insulating materials in floor and roof panels further enhances sound insulation particularly useful in multi-story properties to reduce sound transmission through solid building elements. The airtightness of SIP buildings minimizes air infiltration and enhances insulation, maintaining consistent indoor temperatures and reducing the need for heating or cooling. This leads to lower construction costs and ongoing savings for the owner. SIPs construction is favored by builders like Matrod Frampton and Frame Homes for its simplicity and speed. With fewer components and insulation already included, SIPs save time up to 50% compared to traditional timber buildings as per Building Research Enterprise. This means potentially completing two more projects per year and lowering labor costs for clients. Buildings constructed with structural insulated panels (SIPs) perform well during earthquakes due to the high mechanical strength and low flexibility of the panels. Research in New Zealand confirms SIPs as an innovative solution for seismic design. It is important to assess different building systems respond to ground motion during earthquakes. Maintaining a certain level of flexibility in the structure helps prevent excessive damage. SIPs have low flexibility which means that they deform only under extreme stress, enhancing long-term durability. In a 7.1 magnitude earthquake in 2010, SIP-built structures proved seven times more resistant to shear loads than conventional buildings. The joints and nails in SIP systems absorb and distribute deformations reducing the impact of seismic forces. SIPs meet seismic design standards set by the American Society of Civil Engineers making them suitable for any seismic category. SIP roofing systems effectively distribute seismic forces minimizing risks and ensuring stability. The success of SIPs based roofing systems in earthquake prone areas increases the popularity and applicability of SIPs in construction. Further studies confirmed SIP walls can withstand large drifts without permanent damage unlike traditional light frame walls that may suffer cumulative damage. SIPs offer significantly higher racking resistance compared to timber frames. Their dense foam and solid wood construction provide up to seven times more strength. For instance, in tests, SIPs have supported weights exceeding 6,000 lbs whereas stud walls and wooden frames fail at much lower weights. This enhanced structural integrity can result in decreased maintenance needs and lower susceptibility to damage from seismic activity and strong winds. The improved efficiency in production and shorter manufacturing cycles have led SIPs manufacturers to cut costs. Even a small reduction in panel manufacturing time can result in significant labor savings annually. Additionally, quicker turnaround times for manufactured products allow modern SIPs manufacturers to offer cost-effective customized solutions in various sizes and shapes catering to unique or non-standard building designs. Nowadays, the adhesive that joins the facings to the insulating core is applied continuously, significantly reducing the number of adhesive fumes in the factory. In recent times, technological advancements have transformed the SIPs manufacturing process making it considerably more efficient. The latest production lines are highly automated and employ multi-head, high-pressure laminating presses. These presses can simultaneously bond the three layers of the SIPs sandwich with tremendous pressure across the entire panel surface with each press capable of producing a complete panel in around twenty minutes. Multiple presses are typically used in a production line to achieve a high production rate.

## IV. SIPS APPLICATIONS

In the past few years, there has been a rising concern for the environment and a desire for environmentally friendly products. This has played a major role in the recent popularity of SIPs which are recognized as one of the most environmentally friendly building methods. This is mainly because SIPs offer enhanced insulation and airtightness leading to improved energy efficiency and decreased reliance on fossil fuels. Additionally, the versatility of SIPs has allowed them to be extensively used for temporary structures, disaster relief shelters and even in the aerospace industry. Structural insulated panels (SIPs) offer a sturdy and consistent building material choice for constructing tall buildings. SIPs are robust and exhibit high modulus and shear strength when subjected to seismic loads. These panels typically consist of oriented strand board (OSB) skins and a foam core. As compared to other structural materials, SIPs are lightweight which reduces the seismic forces acting on the structure and consequently lowers the risk of earthquake damage. This seismic resilience can lead to significant cost savings for high-rise building owners through reduced insurance premiums. SIPs can be tailored to specific design requirements allowing for customization in terms of panel dimensions, thickness, surface materials and insulation methods, making them adaptable to various climates. SIPs are commonly used for walls and roofs in high-rise construction helping to decrease the weight of the building envelope particularly at higher levels, thereby reducing seismic shear forces and overturning moments. Moreover, since SIPs are prefabricated with minimal on-site work required, they contribute to improved worker safety during earthquakes. The prefabricated and pre-insulated nature of SIPs accelerates construction timelines resulting in significant labour and management cost savings. Ultimately, integrating SIPs into high-rise building projects can lead to long-term cost reductions by minimizing disaster and maintenance expenses over the lifespan of building. The initial costs may be slightly higher compared to traditional methods typically ranging from 1% to 5%, the long-term advantages offered by SIPs far outweigh this initial investment. The rapid construction rate enabled by SIPs not only reduces labour expenses but also accelerates the return on investment from the completed project. Research by the Structural Building Components Association indicates that over a five-year period, opting for SIPs instead of traditional timber framing could yield up to $400,000 in savings for a project owing to various factors. For instance, SIPs installation often experiences lower labour costs due to the swift installation process of panel and straightforward system. Furthermore, the shortened construction duration typically leads to quicker returns on investment compared to traditional methods. SIPs cost effectiveness and energy efficiency savings position them as a viable long-term solution for reducing building operational expenses and ensuring compliance with modern standards. SIPs offer remarkable versatility allowing them to be easily customized to accommodate various design elements like vaulted ceilings and steeply pitched roofs. Dissimilar to traditional methods, SIPs can be shaped to fit curved walls or complex architectural designs with relative ease. This flexibility empowers architects to unleash their creativity and bring almost any architectural vision to life. Designing with SIPs enables the creation of tailored solutions maximizing internal space while enhancing thermal performance by minimizing thermal bridging. Additionally, utilizing SIPs can streamline the design process and minimize errors since the same company oversees SIP production, on-site construction and the creation of necessary openings.

## V. CONCLUSION

SIPs stand out as an environmentally friendly building option for several reasons. Firstly, their production process generates significantly less waste compared to traditional wood framing methods. SIPs are precisely cut to size at the factory minimizing job site waste and reducing the need for waste disposal. Far apart from conventional construction, where a standard home can produce a substantial amount of waste. SIPs contribute to a cleaner and more efficient building process. Additionally, SIPs create a tightly sealed and well-insulated building envelope leading to reduced energy consumption in buildings. This not only transfer to cost savings for building owners and occupants but also contributes to environmental conservation. As buildings use a large amount of global energy, cutting their energy consumption can reduce financial costs and environmental impacts including greenhouse gas emissions. The growing emphasis on environmentally responsible building practices includes the adoption of energy-efficient construction materials which increase the use of SIPs in construction projects. The increasing popularity and widespread acceptance of SIPs in the construction sector are inevitable. Apart from saving builders time and resources, SIPs contribute to creating more comfortable living spaces. They significantly reduce worksite waste leading to a cleaner and quieter construction process with minimal disruption from traffic. SIPs are typically manufactured under adverse factory conditions leveraging modern technology to produce custom panels tailored to client specifications. Advanced cutting machines and software ensure precise fabrication with the aid of computer-aided design and computer-aided manufacturing (CAD/CAM) systems enhancing efficiency. The versatility of SIPs extends beyond residential buildings to various other structures like pools, gyms, clinics and hotels. However, the success of SIP projects relies heavily on experienced designers and installers familiar with SIP applications. With technological advancements in fabrication processes and the environmental and cost-saving benefits SIPs offer both industrialized and developing countries are increasingly adopting their use. SIPs not only speed up the realization of dream homes but also provide energy efficient and comfortable living environments making them favoured materials in the construction industry.

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