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Experimental study of thermal and airtightness performance of structural insulated panel joints in cold climates

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ABSTRACT

The extreme climate and limited nature of local resources in the arctic create serious challenges for the many Inuit communities. Homelessness and housing shortages are still common, underlining the need for the construction of durable, sustainable, and affordable housing. The building envelope is highly susceptible to moisture damage and deterioration if not well designed and constructed, especially in the arctic. For this project, the thermal and airtightness performance of structural insulated panel (SIP) joints are studied.

A full-scale test hut built with SIPs was constructed and tested in an environmental chamber at −20 °C and −40 °C, simulating arctic conditions. Eight types of SIP joints were monitored with thermocouples, with at least 6 thermocouples per joint. The SIPs were subjected to temperature differences of up to 62 °C and pressure differences up to 15 Pa. It is found that joints connecting three envelope elements are leakier and more susceptible to moisture damage than those connecting two. Though all joints are dependent on the tape seal to maintain airtightness, it is more difficult to ensure good air seal for the more complex joints. All the joints can be improved to be less dependent on the tape, though the joints most susceptible to moisture damage and mold growth are the top joints since moist indoor air tends to exfiltrate at those locations due to stack effect.

1. Introduction

Northern Canadian communities undergo many challenges to sustain themselves and housing is one of the major ongoing problems. Permanent housing in Inuit communities began in the mid-1950s as a result of a number of factors including the introduction of compulsory schooling, the end of the fur trade, and outbreak of infectious diseases [36]. This almost immediately sparked the housing crisis, where the Nunavut Housing Corporation was confronted with problems of suitability, adequacy, and affordability. Developing and maintaining wood-frame housing in the arctic is much more demanding than in the south. All the material needed to construct wood frame houses cannot be obtained locally, so they must be shipped from southern Canada. The same goes for skilled labor, which is flown over from the south. There is an almost complete dependence on fossil fuels for energy since diesel generators are used to produce electricity. Residential construction costs are 1.3–3.6 times higher than in larger southern cities [22]. Consequently, housing shortages and crowding are common issues in many communities [34]. A survey of 1901 Inuit households showed that 30% of Nunavut households were crowded [18]. Existing houses have exhibited numerous and systemic issues caused by poor design and construction. It was also found that 40% of surveyed Inuit homes were in need of major repairs, while 20% reported mold problems. Accelerated deterioration of these houses is caused by a number of factors including the extreme conditions, substandard building materials and construction, culturally inappropriate housing designs, and overcrowding. Therefore, housing developments must follow minimum requirements specifically tailored for the arctic to ensure suitability and durability [37].

Recent efforts have been made to build sustainable housing for the North made of structural insulated panels (SIP). SIP houses can be built quickly and easily [20], and a number of studies have identified SIP construction as one of the suggested high performance building envelopes for the arctic [2,7,9,29]. SIPs are a building system intended for high performance housing and lightweight commercial construction. SIPs are made of a rigid, insulating core material sandwiched between two layers of

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structural board, bound using an adhesive. The insulating core is often made of expanded polystyrene (EPS), extruded polystyrene (XPS), polyisocyanurate (PIR), or polyurethane (PU). The structural boards are commonly made of plywood, oriented strand board (OSB), sheet metal, or cement. As the name suggests, SIPs provide the structural support and thermal insulation for a building, but can also act as the air and vapor barrier. The thickness of SIPs generally depends on the insulation requirements of the building.

SIPs have been extensively examined with regard to their structural performance [14,19,33,35], though experimental studies on the hygrothermal performance of SIPs is still very limited, especially for joints. A study by Ref. [26] subjected steel faced SIPs with either PU, rock wool, or glass wool insulation to outdoor climates of French Guiana and Finland for one year. Condensation was found on the inner steel facing in French Guiana and on the outer steel facing in Finland. PU insulation had the best thermal and moisture performance of the three. Ref. [25] investigated the use of hygrothermal simulation software to aid in the design of a novel SIP with an innovative support system, ensuring good performance with regards to building physics. The constructed SIP was then monitored in the field and the results agreed well with simulation, which showed that simulation can be used to develop hygrothermally safe construction.

Existing studies through both experiments [3,10,11,13,17,27,30,32] and modeling [15,23,28,40,41] indicate that imperfections and consequential air leakage in the building envelope have significant impact on the hygrothermal performance of building envelopes. Similarly, the weak spots of SIPs, and prefabricated envelope systems in general, are often the joints, not the main section of the panel or panelized system. Thermal bridging and air leakage at the joints of prefabricated constructions have become more important with regards to hygrothermal performance, though studies are scarce. Ref. [24] reviewed the current status of SIPs as a building material, concluding that improving the thermal performance and airtightness of SIP joints is a key milestone for the future of SIPs. Ref. [1] conducted an experiment to evaluate the thermal performance of 25.4 mm (1″) and 76.2 mm (3″) fiber-reinforced plastic panels, a type of SIP. Thermocouples and test plates were used to find the heat flux through the center of the panels as well as the joints, with and without the joint sealant. The overall R-values of the panels increased by 5–46% after the joints had been sealed, which shows how significant the influence of air leakage can be and that the tightness of the joints without sealant can vary considerably. The study was limited to one type of joint and did not consider the effects of air pressure. One field study by Ref. [4] recognized the importance of the heat, air, and moisture performance of joints in prefabricated construction. In this study, a house in New Brunswick composed of prefabricated, panelized wood-frame walls was monitored for two years with temperature, relative humidity, and differential pressure sensors at the joint and the clear areas of the panels. Findings included that the air leakage occurred mainly at the joints, while little evidence of moisture accumulation was found. The authors also remarked on the lack of existing studies on the hygrothermal performance of prefabricated construction. Ref. [21] investigated the cost-effectiveness of sealing the SIP joints of a net-zero house, known as Equinox House. They measured the air leakage rate of the building at 50 Pa at several stages during the caulking process. The ACH of the house at 50 Pa before and after caulking the joints were 3.0 and 0.5, respectively, indicating a heavy reliance on the joint sealing for airtightness. They also indicated the lack of information on the air leakage characteristics of specific SIP joints, such as wall to wall, wall to floor, and wall to roof.

At Summit Station, Greenland, an administration building composed mainly of SIPs was examined for its thermal performance after more than 20 years of service [6]. The SIP walls were 127 mm thick, constituting of a PIR insulation core and OSB facings. An IR camera and blower door were used to inspect the thermal performance of the envelope, while data loggers recorded temperature and relative humidity data indoors. IR imagery showed that the joints between the walls and the roof exhibited noticeable thermal bridging, less so elsewhere. The joints between the SIP walls were found to leak very little air, even after the building had been lifted on its steel supports several times over the years. Given its age, the building was found to perform very well. There have also been reports of SIP houses failing in arctic climates. SIP houses built in Juneau, Alaska encountered moisture problems in their roofs only six years after construction [31]. Improper sealing of the joints allowed warm, moist air to migrate through the joints and condense at the exterior facing. The occurrence emphasizes the importance of design and workmanship for these building systems to perform as expected.

The thermal performance of SIPs and SIP joints in extreme cold climates has been investigated experimentally recently [38,39]. An inverted SIP test hut, where the cold conditions, as low as −30 °C, were reproduced inside the test hut and exterior conditions were the ambient room conditions, provided the experimental setup. Several thermocouples were installed along the thickness of the SIPs, both near the center of the panel and at the joint between two aligned wall SIPs. The results showed that air leakage was found to be the most significant cause of heat losses through the joints, and that air leakage caused by defects and cracks in the joints are the most likely failure mechanism for this system. However, tests with pressure differentials were not conducted in the study. The authors' suggestions for future work include studying the panels at lower temperatures, carrying out tests with higher indoor relative humidity levels to reflect overcrowding in homes, and to test other connections like wall-to-roof and wall-to-floor, which are not possible with the inverted test hut setup.

Literature indicates that there are significant gaps with the evaluation of SIPs. Though it is known that SIPs are most susceptible to heat, air, and moisture problems at the joints, there have been no studies investigating the performance of the many joints formed by SIP assembly. Since the SIP system is destined for arctic climates, they need to be evaluated under corresponding conditions. In the interest of addressing these gaps, the objective of this study is to evaluate experimentally the thermal and airtightness performance of SIP joints subjected to arctic temperature conditions as well as pressure differences.

2. Methodology

This section consists of the description of experimental setup including the full-scale SIP test hut, instrumentation, test conditions and the thermal simulations.

2.1. Full-scale SIP test hut

A full-scale test hut (TH) was constructed and tested in an environmental chamber (EC), as shown in Fig. 1. The TH design, shown in Fig. 2, is based on the prototype SIP duplex built in Iqaluit, Nunavut. The SIP Duplex design is based on, and improves upon, the 142 SIP houses that were constructed across Nunavut to address the housing crisis. Table 1 compares the insulation and airtightness characteristics of the SIP houses and test huts related to this study. The last column of the table shows the values recommended by the Government of Nunavut [12].

The TH walls and floor are composed of SIPs while the roof consists of trusses supporting an attic insulated at the ceiling level. Based on a rectangular cuboid shape, the TH measures 4.27 m by