Canada Wood
Produits de bois canadien

Thermal Performance

of Light-Frame Assemblies

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Introduction

"A man's home is his castle" is an old familiar phrase, but if truth be told, the castles of old were cold and draughty. Today's homes are now havens of comfort with efficient central heating systems and well insulated building envelopes. We count on the walls and roofs of our houses to keep the heat in during the winter months and the heat out during the sweltering days of summer. Today's home buyers demand energy efficient houses with high insulation values. "Lowering energy use" has become the goal as the cost and environmental implications of energy use are considered.

Insulation levels are now being required by many code authorities. Stricter thermal requirements mean that designers must understand the impact of the materials and assemblies used on thermal performance.

Because of its long history of use, wood-frame construction has well established insulating properties and record of performance. The effect of other construction systems on insulation properties is not widely known or understood. This publication will examine current knowledge of the thermal performance of wood and other framing techniques.

This information will assist designers and builders to select construction techniques that provide the best thermal performance.

Thermal Performance

In temperate climates, almost 20% of total energy consumption is used for the heating, cooling, and lighting of residential buildings. This energy use is costly but the use of selected materials and building systems can help to improve the overall thermal performance of our buildings.

Heat Transfer Defined

Heat always moves from a warm area to a cold area. Heat flows from the interior through the building envelope to the exterior in the winter, and from the exterior to the interior in the summer. Heat flow to and from the building cannot be stopped altogether, but can be minimized by using a combination of materials that resist heat flow. Heat is transferred in the following ways:

1. Conduction occurs in a solid material when the molecules are excited by a heat source on one side of the material. These molecules transmit energy (heat) to the cold side of the material. Conduction occurs primarily through the foundation and framing members in buildings. The rate of heat flow depends on the materials used.

2. Convection is the movement of air that occurs as heated air becomes less dense and rises, and cooler air is drawn in to fill the space left by the displaced heated air.

3. Radiation occurs when one object transfers heat to another object by releasing heat waves. For example, the sun produces radiant energy that heats the earth. Radiation can affect surface temperatures of buildings, but affects heating requirements mainly through glass windows and doors.

4. Air currents can carry hot or cold air and depend on the pressure differences between the interior and exterior of the building, as well as air leaks in the building envelope. Although this sometimes results in convection, air leakage can also move directly through small openings into walls or roofs. This can carry water vapour into wall cavities and lead to condensation.

All four types of heat transfer affect buildings. However, most heat loss in tightly constructed buildings occurs by conduction through the building components. To maximize energy efficiency, building assemblies must be designed using framing materials that resist heat flow, and must include continuous air barriers, insulation materials, and weather barriers to prevent air leakage through the building envelope (see Figure 1).

An **air barrier** is a membrane that restricts the migration of air into and out of a building envelope. This is to control heat loss through uncontrolled air leakage, but also to ensure that unwanted moisture is not carried into wall or roof openings.

In typical frame construction, air leakage is possible where services, vents, and pipes traverse exterior walls and ceilings. The applied air barrier must be durable, strong and continuous throughout the building envelope, and properly installed to resist the pressure differences from wind, ventilation, and air movement. For example, a 0.15 mm polyethylene membrane placed on the inside of framing members, caulked, and tightly held in place by the application of gypsum board constitutes an air barrier. Another example is a spunbonded polyolefin "housewrap" membrane with taped joints, applied to the outside of wall sheathing.

FIGURE 1: Maximizing Energy Efficiency

A continuous air barrier applied over wood-framing and insulation significantly improves the thermal performance of a building by reducing air leakage.

Overlapping of the air barrier, together with caulking around this ceiling air vent, helps to prevent air leakage through the building envelope.

A weather barrier applied to the exterior sheathing prior to siding materials, acts as an additional barrier against wind, rain and snow.

Source: John W. Wren Holdings Ltd.

In colder climates, both the interior polyethylene membrane and the exterior "housewrap" membrane are used together. That is because the polyethylene air barrier is also a vapour barrier and the exterior "housewrap" is also a weather barrier. In cold climates, vapour barriers are placed on the warm side of the insulation to prevent vapour from diffusing through the interior wall or ceiling finish, and then cooling and condensing within the wall or roof assembly.

The polyethylene should not be used on the outside of houses in colder climates because it would trap any moisture in the wall assembly. The "housewrap" type material is not a vapour barrier, making it suitable for use on the outside of the house.

Insulating materials placed within the wall, roof, or floor cavities slow the rate of heat transfer from warm to cool areas. Their efficiency is based on reducing conduction of heat through air pockets in their composition, and by minimizing convection by keeping the air pockets small. Common insulating materials are made from various materials including mineral or glass fibers and expandable foams.

A **weather barrier** is a membrane placed on the exterior sheathing as a first defense to protect the envelope from wind, rain, and snow. In some cases, this includes the "housewrap" type membrane or other types of sheathing paper used as an air barrier, but such membranes must be installed continuously with flashing around wall openings to ensure good drainage.

The obvious consequence of using assemblies with poor thermal performance is the requirement for additional energy to heat and cool a building. In addition to the negative environmental impacts, this increased use of energy translates into an increased cost to the building owner that continues for the life of the building. Proper design techniques must be used to increase the energy efficiency and durability of a building.

Wood: A Natural Thermal Insulator

Wood is a natural thermal insulator due to the millions of tiny air pockets within its cellular structure (see Figure 2). Since thermal conductivity increases with relative density, wood is a better insulator than dense materials.

Softwood has about one half the thermal insulating ability of a comparable thickness of fiberglass batt insulation, but about 10 times that of concrete and masonry, and 400 times that of solid steel. However, although wood has the best insulating properties of the primary framing materials, wood construction techniques are based on the inclusion of efficient insulating products within a wall, roof, or floor structure (see Figure 3).

Due to its air pocket composition, wood is also an effective acoustical insulator and its structure helps to dampen sound vibrations.

FIGURE 2: Microscopic Wood Structure

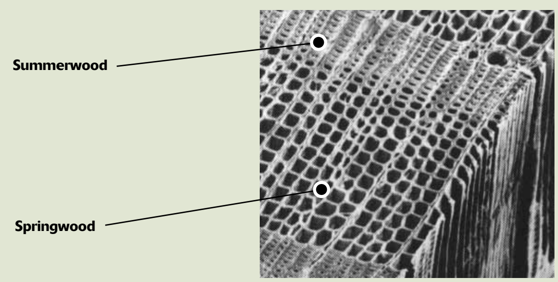


FIGURE 3: Thermal Resistance of Common Materials (RSI/mm)

Sheet steel	no significant resistance
Concrete	0.001
Lumber and structural wood panels	0.009
Gypsum board	0.006
Fiberglass insulation	0.022
Mineral fiber insulation	0.024

Source: Canada Mortgage and Housing Corporation

Effect of Framing on the Insulating Value

The resistance to heat flow of building envelope assemblies depends on the characteristics of the materials used. The ease with which the materials resist heat flow is called the thermal resistance (RSI). The thermal resistance is expressed as an RSI-value with units of $m^2\ {}^oC/W$. The higher the RSI-value, the higher the resistance to heat flow. The thermal transmission (U) is the inverse of the thermal resistance of the assembly.

Insulated assemblies are not usually homogeneous throughout the building envelope. In wood or steel-frame walls or roofs, the framing members occur at regular intervals, and, at these locations, there is a different rate of heat transfer than in the spaces between the framing members. The framing members lower the thermal efficiency of the overall wall or ceiling assembly. The rate of heat transfer at these locations depends on the thermal or insulating properties of the framing material. The higher rate of heat transfer at framing members is called thermal bridging.

The insulating value of an assembly has traditionally been expressed in terms of the nominal RSI-value that is specified on the insulation materials to be used in the assembly. In other words, the RSI-value was based on the insulation alone. In general, this approximation works well to express relative insulating properties only if the framing systems are the same.

But the thermal performance of an assembly depends on the combined effect of the framing and insulation. The thermal properties of the framing materials, which can account for 20% or more of the surface area of a wall, can have a significant effect on the thermal resistance of an assembly. New energy codes recognise this and require that the *effective* RSI-value be used to meet their requirements.

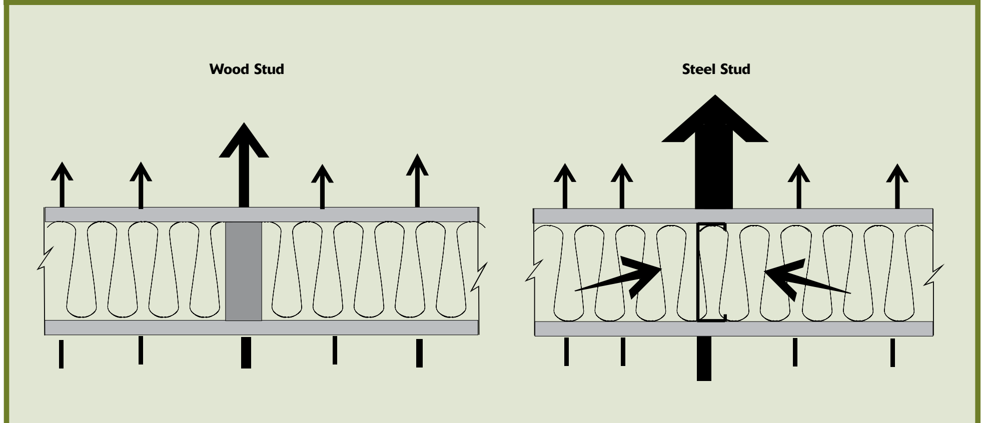
The effective RSI-value is the measured thermal resistance of an assembly. It takes into consideration the thermal effect of all the materials in the assembly. In framed assemblies, the framing members act as thermal bridges. Their effect is calculated and combined with the insulating value of the spaces between the members to determine the overall resistance to heat flow of the assembly, expressed as the effective RSI-value. The effective RSI-value can be used to compare the thermal resistance of different systems.

The overall thermal efficiency of wood-frame assemblies is lowered by the amount of area occupied by the framing members. For most wood-framed assemblies, the effective RSI-value is approximately 90% of the RSI-value of the cavity insulation.

In steel-frame assemblies, heat does not flow in parallel paths because steel has a high thermal conductivity. Heat flows not only through the assembly from the inside to the outside of the building envelope, but also moves from the centre of the insulated cavity to the framing members. Heat flow is therefore concentrated at the steel stud (see Figure 4).

The steel framing member has a much larger effect on the transmittance of heat through the assembly than its own width, and acts as a thermal bridge through the insulation. This thermal bridging results in an effective RSI-value for steel-framed assemblies of 50 to 60% of the RSI-value of the cavity insulation.

FIGURE 4: Heat Flow Through Wood and Steel



Note: Heat flow lines each represent an equivalent amount of heat flow through wall.

Energy Conservation and Wood Frame Construction

Wood frame construction techniques have evolved over the past few decades to meet new energy conservation targets.

For example, a program called R-2000 was developed by Natural Resources Canada in partnership with Canada's residential construction industry, to set a new standard for energy-efficient housing. Building to R-2000 specifications exceeds building code requirements, consuming less energy and producing less greenhouse gases. R-2000 homes also incorporate advanced fresh air ventilation systems, window performance requirements, and environmentally improved building materials.

Another program sponsored by the Government of Canada is the Super E House Program for countries other than Canada. The Super E House Program, supported by Canadian technology, expertise and training, has been introduced into the United Kingdom, Ireland, and Japan.

For more information on the R-2000 Program and the Super E House Program visit *http://www.oee.nrcan.gc.ca/r-2000* and *http://www.super-e.com*, respectively.

There are two aspects to energy conservation in buildings: embodied energy, and operating energy.

Embodied Energy

The "embodied energy" in buildings means the energy consumed in the acquisition of raw materials, their processing, manufacturing, transportation to the site, and construction. The *initial* embodied energy has two components. The direct energy, that is the energy used to manufacture and transport building products to the site and to construct the building.

The indirect energy is the energy use associated with processing, transporting, converting and delivering fuel and energy to its point of use.

The *recurring* embodied energy in buildings represents the non-renewable energy consumed to maintain, repair, restore, refurbish or replace materials, components or systems during the life of the building.

While it is simpler and more common to focus solely on the conservation of operating energy, the effects of embodied energy can be significant in structures. The Canadian Wood Council has published an Environmental Impact Study that demonstrates the impact of embodied energy of structures on the environment in terms of global warming potential, air and water pollution, and solid wastes.

Today's comparisons of embodied energy and the operating energy of buildings over their life-cycle are dominated by the operating component. However, as buildings become more energy-efficient and as we move away from fossil fuels as an energy source, the ratio of embodied energy to lifetime operating energy consumption becomes more significant.

TABLE 1: 1970 Construction vs R-2000 Design

Building Component	1970's Example Construction	R-2000 Design Example
Floor area	$207.4m^2$	$207.4m^2$
Design Life	30 years	30 years
Primary structure	Wood frame construction, concrete basement	Wood frame construction, concrete basement
Envelope	38 x 89 mm studs (GRN), RSI-2.1 fibreglass batt insulation	38 x 140 mm studs (KD), RSI-3.5 fibreglass batt insulation
Windows	Wood windows, standard double glazed	PVC windows, low-E, double glazing, argon fill
Exterior cladding	Brick	Brick
Roofing System	Wood frame truss, asphalt shingle, RSI-3.5 fibreglass batt insulation	Wood frame truss, asphalt shingle, RSI-8.8 fibreglass batt insulation

Operating Energy

The need for saving energy by reducing operating energy consumption in buildings is widely recognized throughout the world.

In Canada, the residential energy consumption decreased by 40% over the last three decades. A life-cycle environmental impact comparison of a 1970 and R-2000 house design was done by the Athena™ Sustainable Materials Institute in partnership with CANMET Energy Technology Centre and Natural Resources Canada.

The Athena™ Sustainable Materials Institute compared the environmental performance including embodied environmental effects for single-family home designs as typically built in Canada from the 1970's through to the present. The study was based on the "as built" design of the Canadian Centre for Housing Technology houses located on the National Research Council's property in Ottawa, Ontario. Specifications for the same house as it would have been built in the 1970's were compared with today's R-2000 compliant construction. (See Table 1).

Operating energy efficiency in residential and commercial buildings is greatly enhanced in highly insulated and airtight building envelope systems, high performance windows, high-energy efficiency heating, cooling and water heating equipment, low energy lighting and Energy-Star home appliances.

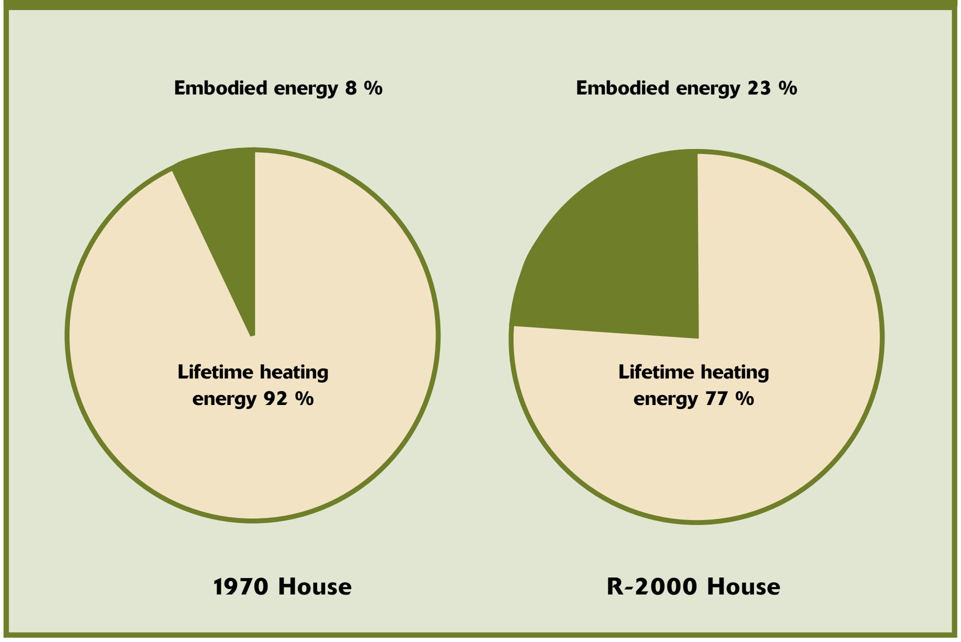
The increased insulation in foundations, walls and attics, and insulated doors and windows contributes greatly to reduce the operating energy in buildings, however, it requires the use of more materials with a higher embodied effect.

The annual space heating for the R-2000 home is only 27% that of the 1970's home (a factor of 4 decrease). Total R-2000 annual operating energy use is 42% that of the 1970's design, and the total 30-year life cycle energy for the R-2000 house is only 46% that of the 1970's design. About half of the total improvement in operating efficiency can be ascribed to better envelope design, with the remainder a function of higher mechanical equipment efficiency.

As noted earlier, embodied energy effects become more significant as the operating energy requirements of buildings are reduced (see Figures 5). This is also influenced by the increased material requirements to build the R-2000 home.

When embodied effects are combined with those of space heating, the R-2000 house ends up using 60% less energy and emits 61% fewer green-house gases over a 30-year time period.

FIGURE 5: Embodied Energy vs. Lifetime Heating Energy



Thermal Performance of Wood vs. Steel

Steel conducts heat 400 times faster than wood. But since a steel C-channel stud is much thinner than a wood stud, a 20 gauge steel stud conducts approximately 10 times more heat than a 38 mm wide wood stud. The thermal performance of framed systems has been studied extensively in the laboratory and in houses. The results demonstrate the superior performance of wood framing systems.

Laboratory Research Results

Wood framing has a long history of use. Based on testing and performance, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) Handbook of Fundamentals, uses a procedure for calculating effective thermal resistance for parallel path heat flow. The RSI-value is calculated at the framing (R_F) and at the insulation (R_I) and then the average effective RSI-value (R_E) is determined based on the area of each, as a ratio of the total area.

Laboratory research into the performance of steel-framed walls conducted in Canada by the National Research Council's Institute for Research in Construction (IRC), and in the U.S. by the National Association of Home Builders (NAHB) Research Centre and the Oak Ridge National Laboratory, shows that the assumption of parallel path heat flow does not apply to steel-framed systems.

The laboratory tests use a hot-box method which tests clear wall systems that are isolated from any other parts of the structure. These tests have confirmed that steel studs severely lower the effective RSI-value of the assembly. Recently, IRC measured the RSI-value of three steel stud wall assemblies. The research determined that for the steel-stud wall assemblies the effective RSI-value is approximately half that of the insulation. In other words, the presence of the steel studs substantially reduces the overall performance of the whole assembly.

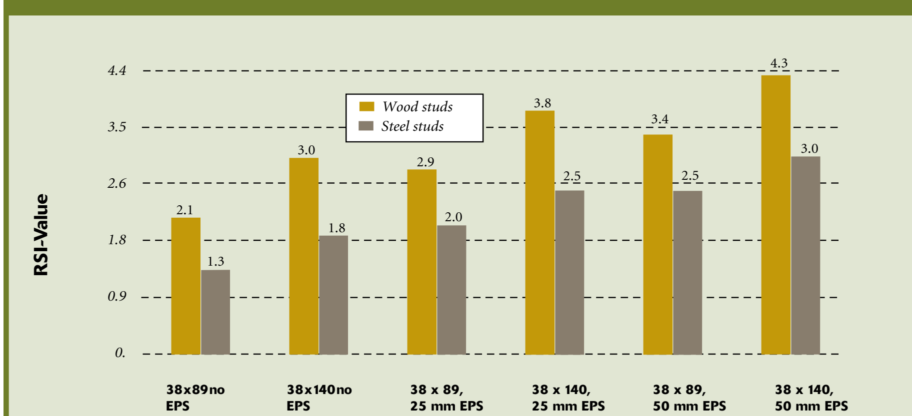
Adding insulation to the outside face of the steel studs will contribute only its own RSI-value; it does not completely negate the effects of the steel in the wall assembly, and there is obviously a cost for the extra insulation.

The Canadian National Energy Codes use a rigorous calculation method developed by the IRC for determining the effective insulation values for most of the common wall, roof and floor assembly configurations. As shown in Figure 6, steel framing lowers the effective RSI-value of the cavity insulation by close to 50%, while wood framing impacts the effective RSI-value by less than 10%. In other words, a 38 x 140 mm steel-frame wall would need an additional 51 mm of foam insulation to achieve the same insulating value as a wood-frame wall with cavity insulation.

Effective RSI-values for steel-framed assemblies are much lower than wood-framed assemblies filled with the same insulation materials. Steel-framed assemblies require high thermal resistance contribution from exterior foam sheathing to achieve the same effective RSI-values as wood-framed walls without foam sheathing. This results in increased costs to achieve the same performance.

HOT2000 is an energy analysis program for residential buildings developed by Natural Resources Canada and is available at: *www.buildingsgroup.nrcan.gc.ca*. The program enables designers to evaluate the energy usage of various building designs.

FIGURE 6 - Wood vs. Steel Framing - Effective Insulation Values



Source: National Energy Code for Houses 1995

Field Measurement and Modelling

Reports from the field indicate that the thermal performance of full scale steel-framed houses falls short of the laboratory measurements previously discussed.

The laboratory specimens were "clear" walls with no anomalies such as intersections, window frames or door frames found in standard construction. These laboratory tests were also limited to wall sections that were thermally isolated from other parts of the structure such as roof framing or foundations. The following testing was performed on steel-framed houses, where the performance really counts.

Thermographic Testing

Infrared thermograph shows that, compared to conventional wood-framed walls, steel framing results in major heat loss from the building shell and that switching from steel trusses to wood trusses significantly improved the thermal performance of the attic. Temperatures measured at steel stud locations were 4°C lower than at the cavity locations.

Thermographic testing done by the Bonneville Power Administration in Portland, Oregon on light gauge steel-frame houses, showed walls with plywood sheathing and 18.5 mm foam sheathing to be thermally identical.

Infrared thermography of 140 mm walls with cavity insulation and RSI-1.1 sheathing found interior-wall surface temperatures of 7.3°C over steel studs when the outside temperature was 4.4°C . The study found that the heat travelled down through the steel to the foundation and up to the steel roof structure.

Laboratory testing performed by the American Iron and Steel Institute (AISI) determined that 12.5 mm of foam sheathing would keep the temperature difference between the steel stud and the cavity below 1.6°C. The thermographic field testing of actual houses shows that even with 50 mm of foam the temperature difference between the steel stud and the cavity is 2.3°C.

The field performance appears to be significantly worse than the measured laboratory performance.

Air Infiltration

The Energy Services Group from Wilmington Delaware, noted in the August 1995 issue of Energy Design Update, that the measured infiltration rate of steel-framed walls in houses was approximately 50% higher than the infiltration rate of wood-framed walls.

They attributed this to the holes in the channels used for top and bottom plates in steel wall construction. This provides a large number of infiltration points to the attic. Increased air infiltration also results from the use of "hat" channels used to reduce thermal bridging and sound transmission. The use of the channels creates a slot open to the attic down the full length of the wall allowing for increased air flow.

The discrepancy between laboratory and field testing prompted researchers at the Oak Ridge National Laboratory in Oak Ridge Tennessee to examine the effect windows, doors and intersections of other building components had on the clear wall lab tests.

For the wall system reported in this study, the steel-frame wall effective RSI-value for the entire wall was 19% lower than clear wall values. The wood-frame wall effective RSI-value for the entire wall was 9% lower than clear wall values. The steel-frame wall effective RSI-value was 40% lower than the effective RSI-value for the wood-frame wall when the entire wall was considered.

In summary, the report concluded that the effect of construction features, such as intersections of windows, doors, walls and also connections with roofs and foundations further lowered the thermal performance of steel-framed walls relative to wood-framed walls. Wood-frame construction is clearly superior in terms of overall thermal performance.

Effects of Low Thermal Performance

Ghost Marks on Steel Stud Walls

Ghost marks are unsightly dark vertical marks that appear over the framing on the interior surfaces of exterior walls. A 1971 report from US Steel cited "ghost marks" caused by steel studs as "the single-most significant unsolved technical problem that prevents the general acceptance of steel studs in the residential market. The design of steel studs has not changed, and ghost marking remains a problem.

Contrary to common belief, ghost marks are not caused by moisture condensation and can occur even in a completely dry environment. They are caused because floating dust particles which are constantly moving in every direction absorb energy at a faster rate from warm air than from a cool wall. As a result, the dust particles are propelled towards the cool wall surface.

On a wall with a uniform surface temperature, such as a wood-framed wall, dust accumulation is not noticeable since it spreads evenly over the wall surface. But on a wall with cold spots, such as a steel-framed wall, dust accumulates faster over the colder areas and is visible as ghost marks.

US Steel conducted a series of experiments in the early 1970s to investigate the conditions that cause ghost marks. They discovered that:

- Ghost marks occurred whenever the wall temperature varied by more than 1.8°C, and

- Severe discoloration occurred when the temperature at the steel stud was more than 4.5°C colder than the cavity.

Indoor Air Quality

It is important to build differently with framing materials having high conductivity such as steel studs to avoid localised cold spots at the thermal bridge.

In a letter to the Environmental Building News, Sept./Oct 1995 edition, a Canadian researcher cautioned about the health implications of mould growth at the thermal bridge over steel studs.

Mould is the major indoor contaminant in most homes. Local cold surfaces in higher humidity houses could result in serious mould growth problems after the first few cold months.

The researcher reiterates the importance of reducing the cold spots by placing the insulation on the exterior of the steel framing members to reduce the possibility of mould growth and possible adverse health effects.

Increased Construction Costs

Steel framing requires extra foam insulation on the exterior to achieve the same thermal resistance as wood-framed systems. For example, foam sheathing, 50 mm thick, is required to make a steel-framed wall thermally equivalent to a 38 x 140 mm wood-frame wall. There will also be an increased cost for the extra provisions such as extended window and door jambs.

Increased Energy Requirements and Environmental Costs

In the Montreal area in Canada, for example, a small house with 90 m^2 wall area with 38 by 89mm framing and RSI-2.3 batts, would use an estimated 2900 kW-h per year more if was framed with steel than if it was framed with wood.

The lower thermal performance of steel framing results in increased energy usage for the heating and cooling of buildings. The environmental effects of increased energy usage due to poor thermal performance of steel framing translates into a cost that must be borne by society. This cost is in the form of increased air pollution, increased CO_2 emissions, and additional use of non-renewable fossil fuels.

The use of foam sheathing to increase the thermal performance of steel-frame assemblies also has an environmental cost. Foam sheathing is derived from non-renewable fossil fuels. The manufacture of some types of foam sheathing produces hydrofluorocarbons (HCFC) which cause ozone depletion and use high levels of energy. For example, it takes approximately 1600 kW-hr of energy to manufacture 100 m^2 of 25 mm rigid foam, or enough to clad a 120 m^2 bungalow.

The additional environmental costs of the foam must be included when determining the environmental cost of the steel framing because the foam must be used to achieve the equivalent performance of the wood framing.

Conclusion

Energy requirements for buildings are increasingly important. The thermal performance of a building is becoming not only a desired attribute but a mandated code requirement in many jurisdictions. Recent research and experience with wood and steel-framed systems have examined the issue of thermal performance in detail.

This summarises what has been learned to date about the thermal performance of wood and steel-framed systems:

- Laboratory research of clear walls shows that steel-frame walls have significantly lower thermal performance than wood-frame walls,

- Field research shows that steel-framed houses' thermal performance is worse than the laboratory tests predicted,

- Computer modelling shows that the effect of construction features such as intersections with windows, doors and corners lowers the thermal performance of steel walls even more than comparable wood-framed walls which explains the difference between laboratory and field research,

- Construction methods for achieving thermal performance with steel-framed assemblies should be adjusted to take into account the lower field performance of the assemblies, and

- Steel framing requires additional insulation on the exterior of the framing to achieve the same insulation values as wood-framed assemblies.

The consequences of not providing the additional insulation are higher heating and cooling bills, ghost marks on the walls and deterioration of the indoor air quality due to increased mould growth.

Steel framing systems can be designed to provide an equivalent thermal barrier but the provision of the extra insulation results in increased material and environmental costs for the system. Designers must consider the total performance and cost of a system when making their choice.

Compared to steel and concrete, wood offers superior resistance to heat flow because of its unique cellular structure. Thus, in a building envelope design, wood framing loses less heat through conduction than other building materials.

Also, when wood framing is combined with proper construction techniques and materials including insulation, and air and weather barriers, air leakages are minimized resulting in a net decrease in the energy consumption of the home over its lifetime. When comparing a 1970 wood-frame house construction to an R-2000 wood-frame design, about half of the total improvement in operating energy can be attributed to better envelope design.

In addition, wood is the only renewable building material, and the production of wood products reduces industrial energy requirements and lowers the impact on the earth's environment. Wood-frame buildings are also strong, safe, warm, and cost efficient.

Canada Wood
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For more information please contact our office at:

Canada Wood Head Office
Website: www.canadawood.org

Canada Wood China, Beijing
Room 1507, Kuntai International Mansion,
No.12 B Chaowai Street, Beijing 100020
Tel: (86-10) 5925-1255
Fax: (86-10) 5925-1258
Email: info@canadawood.cn

Canada Wood China, Shanghai
425 Hong Feng Road, Pudong New Area,
Shanghai 201206
Tel: (86-21) 5030-1126
Fax: (86-21) 5030-3241
Email: info@canadawood.cn

Canada Wood Korea
3rd Fl., 203 Bldg., #203-7, Yangjae-dong,
Seocho-gu, Seoul, Korea 137-893
Tel: (82-2) 3445-3835/4
Fax: (82-2) 3445-3832
Email: info@canadawood.or.kr

Canada Wood France (Europe)
8 Esplanade Compans Caffarelli,
31000 Toulouse, France
Tel: (33-5) 62-30-51-42
Fax: (33-5) 62-30-50-00
Email: europe@canadawood.org

Canada Wood Japan
Tomoecho Annex-11 9F
3-8-27 Toranomon
Minato-ku
Tokyo 105-0001, Japan
Tel: (81-3) 5401-0531
Fax: (81-3) 5401-0538
Email: info@canadawood.jp

Canada Wood UK
Suite 8, St-Albans House
PO Box 1, Farnborough, Hants,
United Kingdom
GU14 6WE
Tel: (44-1252) 522545
Fax: (44-1252) 522546
E-mail: office@canadawooduk.org

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