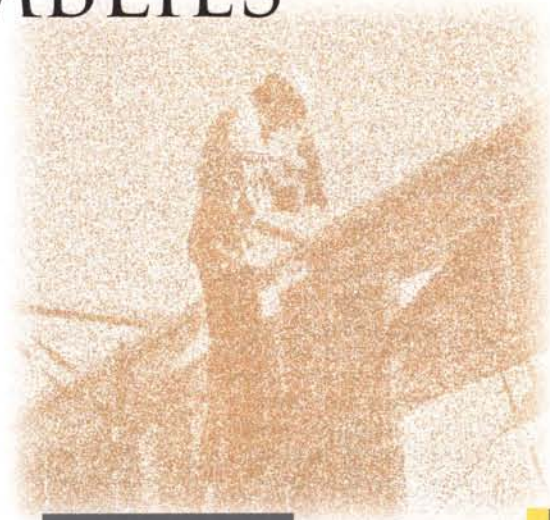


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No. 3



THE THERMAL PERFORMANCE OF LIGHT-FRAME ASSEMBLIES



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THERMAL PERFORMANCE REQUIREMENTS

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.

Home buyers demand energy efficient houses with high insulation values. "Lowering energy use" has become the mantra of the new millenium as the cost and environmental implications of energy use are considered.

Insulation levels are now being prescribed 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, builders and designers are familiar with the insulating properties of wood-frame construction. 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 both wood and steel framing as follows:

- thermal performance requirements
 - effect of framing members on insulating values
 - review of research results of laboratory and field testing of wood and steel-framed systems
 - consequences of low thermal performance

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

In Canada, over 30% of national energy consumption is used for the heating, cooling and lighting of buildings¹. This energy use is costly and has a major impact on the environment. Because the thermal efficiency of buildings can play a significant role in reducing energy consumption, both Canada and the United States have developed model energy codes. These codes regulate the insulation of the building envelope and also the energy efficiency of mechanical systems.

In Canada, the following model codes have recently been developed:

- National Energy Code for Houses (NECH) and
- National Energy Code for Buildings (NECB).

Several provinces have adopted various levels of thermal performance requirements in their codes. The model codes will provide a standard basis for establishing requirements.

In the United States, the Council of American Building Officials (CABO) *Model Energy Code* has been in existence for several years. Federal legislation, in the form of the 1992 Energy Policy Act, requires all state codes to meet or exceed the *Model Energy Code's* minimum insulation requirements.

The model energy codes are intended to minimize energy use in buildings. Energy use for heating and cooling is affected by the thermal performance of all the elements of the building envelope. For this reason, the effect of all the components of the exterior assemblies must be taken into account in determining the insulating value when complying with the requirements of these codes.

The introduction of these codes makes thermal performance of assemblies a design requirement in addition to structural and other code requirements. Designers are faced with the task of selecting assemblies that meet all the performance criteria.

While some designers have always been conscious of thermal performance, energy codes have now made this mandatory for all designers. This has increased demand for information in this area and has resulted in more research for assessing the performance of framing systems. Research results have led to more accurate calculation methods for thermal performance evaluation which will be discussed in more detail in subsequent sections.



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 assist or resist heat flow determines the thermal resistance of the assembly. The thermal resistance is expressed as an R-value with units of $m^2 \cdot ^\circ C/W$ in SI units and $ft^2 \cdot h \cdot ^\circ F/Btu$ in imperial units. The higher the R-value, the higher the resistance to heat flow.

Insulated assemblies are not usually homogeneous throughout. 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 the 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 R-value* of the insulation materials used in the assembly. In other words, the R-value was based on the insulation alone. 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, have a significant effect on the thermal resistance of an assembly. New energy codes recognise this and require that the *effective R-value* be used to meet their requirements.

The effective R-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 R-value. The effective R-value can be used to compare the thermal resistance of different systems.

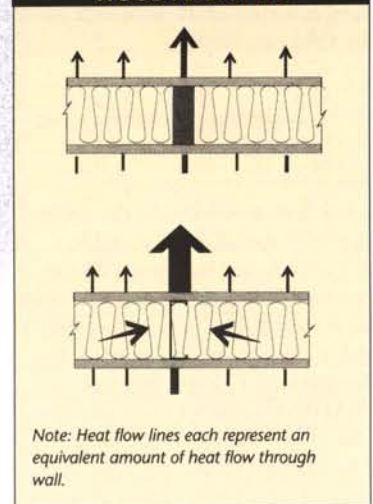
Wood is a good insulator compared to other structural materials. The cellular structure of wood traps air which results in its good insulating properties. Wood, with an insulating value of RSI .008/mm (R1.5/in), is not as efficient an insulator as materials made primarily for insulation purposes such as fibreglass batts. Heat flows through wood-frame walls in parallel lines with slightly more heat flowing through the framing members than the adjacent cavity insulation (Figure 1).

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 R-value is approximately 90% of the R-value of the cavity insulation.

Steel conducts heat 400 times faster than wood. The high thermal conductivity of steel means that heat does not flow in parallel paths through steel-framed assemblies. Heat flows not only through the assembly from inside to outside of the building envelope, but also moves from the centre of the insulated cavity to the framing members. Heat flow is concentrated at the steel stud (Figure 1).

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 R-value for steel-framed assemblies of 50 to 60% of the R-value of the cavity insulation.

FIGURE 1 - HEAT FLOW THROUGH WOOD AND STEEL





WOOD VS. STEEL – COMPARING THE THERMAL PERFORMANCE

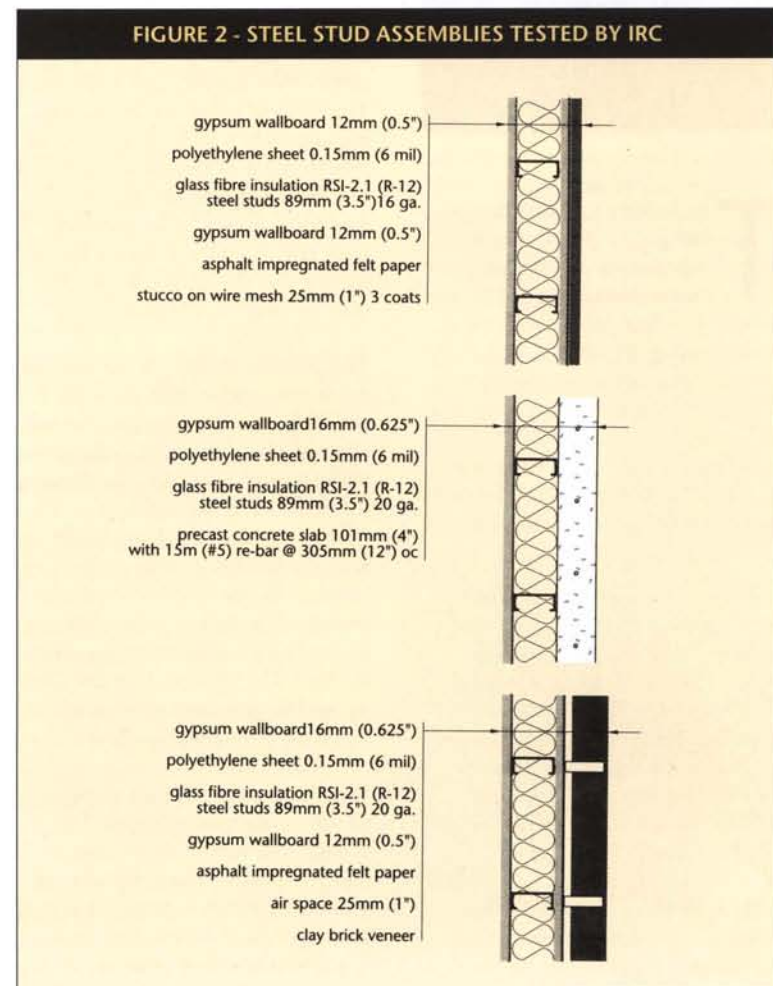
Steel conducts heat 400 times faster than wood. But since a steel C-channel stud is much thinner than a wood stud, a 20 gauge steel stud conducts approximately 10 times more heat than a 38mm (1.5") wide wood stud. Recently, the thermal performance of framed systems has been studied in the laboratory and in houses. The results demonstrate the superior performance of wood framing systems.

LABORATORY RESEARCH RESULTS:

Wood framing has a long history of use and based on testing and performance, the ASHRAE Handbook of Fundamentals uses the following procedure for calculating effective thermal resistance for parallel path heat flow². The R-value is calculated at the framing (R_f) and at the insulation (R_i) and then the average is determined based on the area of each, as a ratio of the total area using the following formula:

$$R_T = \frac{100}{\frac{\% \text{ area with framing}}{R_f} + \frac{\% \text{ area w/o framing}}{R_i}}$$

Laboratory research into the performance of steel-framed walls has been 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. 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 R-value of the assembly. Recently, IRC measured the R-value of three steel stud wall assemblies³ (Figure 2). The research determined that for the steel-stud wall assemblies the effective R-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.

One question raised by these findings is "will insulation added to the outside face of the studs improve the thermal performance of the wall assembly?" The answer is Yes. However, IRC researchers point out that insulation added in this way will contribute only its own R-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.

In the past, heat flow calculations were primarily based on the assumption of parallel path heat flow. The research on steel framing has shown that this assumption does not apply to steel-framed systems. The IRC research developed the following calculation method for clear steel-framed walls in laboratory settings.

THE METHOD INVOLVES FOUR STEPS

1. The effective thermal resistance is calculated as described previously for wood-framed assemblies. (R_{T1})
2. A similar calculation is carried out for those components of the assembly between the planes bounding the inner and outer faces of the metal framing members. (R_{T2})
3. R_{T2} is added to the resistances of the remaining components of the assembly (other than the insulation) to derive R_{T3}
4. R_{T1} and R_{T3} are combined to calculate the effective thermal resistance, R_T , using the following formula:

$$R_T = \frac{R_{T1} + 2 \times R_{T3}}{3}$$

The Canadian National Energy Codes use the rigorous calculation methods developed by IRC for determining the effective insulation values of the framed assemblies. These methods were used in the NEC to develop effective insulation values for most of the common wall, roof and floor assembly configurations. Figure 3 illustrates the relative insulation values for wood framing and steel framing for common wall insulation configurations taken from the appendix of the NEC for houses.

FIGURE 3 - WOOD VS. STEEL FRAMING - EFFECTIVE INSULATION VALUES

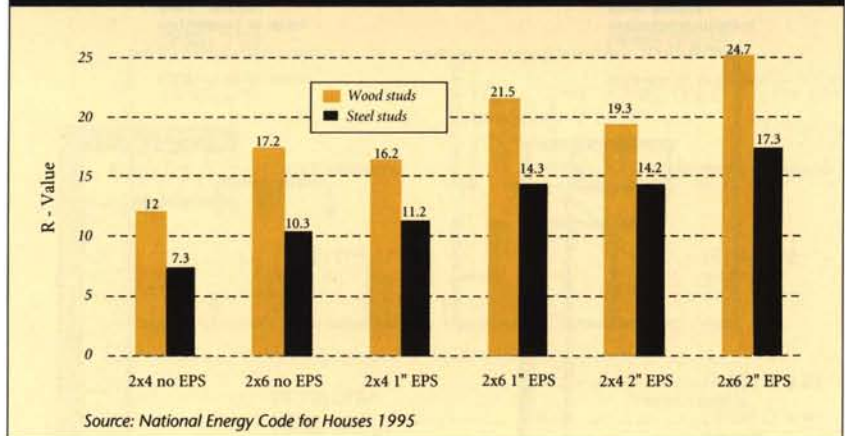


TABLE 1 - CORRECTION FACTOR FOR WALL SECTIONS WITH STEEL STUDS

Framing	Cavity Insulation		Correction Factor	Effective R-value	
	RSI	R		RSI	R
39x89 @ 406mm o.c. (2x4 @ 16" o.c.)	1.9	11	0.5	0.97	5.5
	2.3	13	0.46	1.06	6.0
	2.6	15	0.43	1.15	6.5
39x89 @ 610mm o.c. (2x4 @ 24" o.c.)	1.9	11	0.6	1.16	6.6
	2.3	13	0.55	1.25	7.1
	2.6	15	0.52	1.37	7.8
38x140 @ 406mm o.c. (2x6 @ 16" o.c.)	3.3	19	0.37	1.23	7.0
	3.7	21	0.35	1.30	7.4
38x140 @ 610mm o.c. (2x6 @ 24" o.c.)	3.3	19	0.45	1.52	8.6
	3.7	21	0.43	1.59	9.0
38x184 @ 406mm o.c. (2x8 @ 16" o.c.)	4.4	25	0.31	1.37	7.8
38x184 @ 610mm o.c. (2x8 @ 24" o.c.)	4.4	25	0.38	1.67	9.5

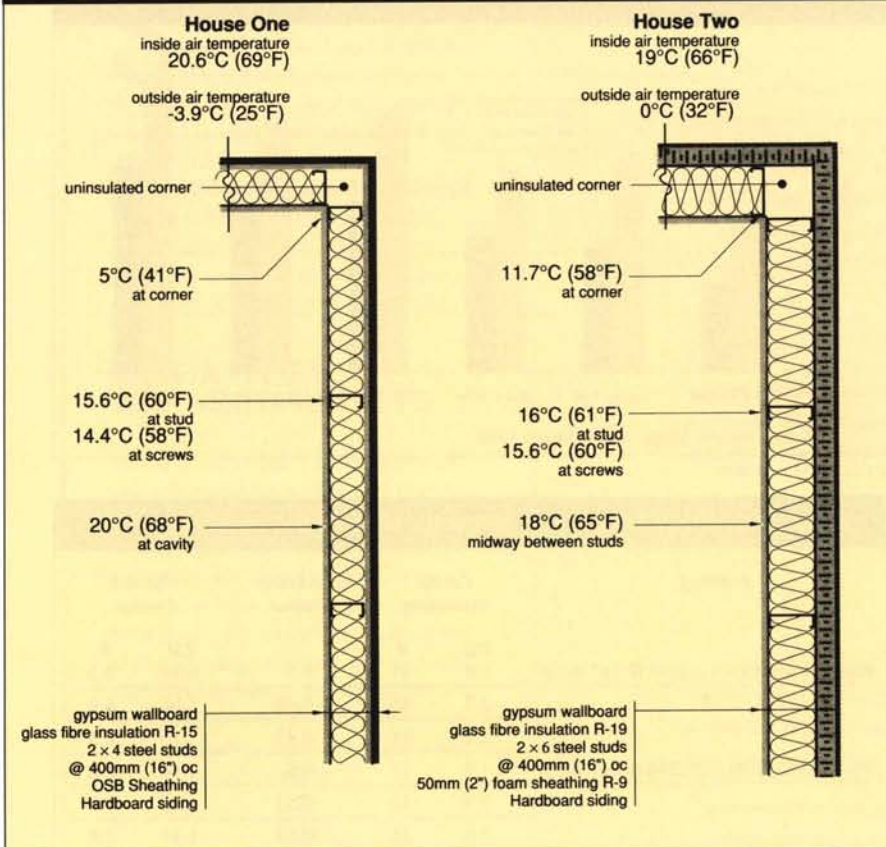
Source: U.S. Model Energy Code

As shown in Figure 3, steel framing lowers the effective R-value of the cavity insulations by close to 50% while wood framing impacts the effective R-value by less than 10%. In other words, a 2 x 6 steel-frame wall would need to add 51mm (2.0") of foam insulation to achieve the same insulating value as a wood-frame wall with cavity insulation only.

In the US Model Energy Code (MEC), the requirements for insulation have been developed based on wood-framed assemblies. A correction factor is applied to assemblies with steel studs to account for the 40-60% loss of insulating value (Table 1). These correction factors are based on ASHRAE tables. Extensive tests,



TABLE 1 - CORRECTION FACTOR FOR WALL SECTIONS WITH STEEL STUDS



funded by the American Iron and Steel Institute (AISI) and performed by the NAHB's Research Centre, confirmed the validity of the ASHRAE correction factors.

In the MEC, the correction factor is applied to the cavity insulation and the insulation value of the foam sheathing is then added to achieve the total effective R-value of the assembly.

The result, using either the Canadian or U.S. methods, is the same. Effective R-values for steel-framed assemblies are much lower than wood-framed assemblies with the same insulation. Steel-framed assemblies require a high thermal resistance contribution from exterior foam sheathing to achieve the same effective R-values as wood-framed walls without foam sheathing. This results in increased costs to achieve the same performance.

FIELD MEASUREMENT OF THERMAL PERFORMANCE

Initial 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:

Steve Andrews, a building science consultant in Denver, Colorado has measured the temperatures of the steel framing members and the cavities of two steel-framed homes using infrared thermography.

Compared to conventional wood-framed walls, his findings (Figure 4) conclude:

- the use of steel framing for exterior elements with either wood panel sheathing or 12.5mm (1/2 inch) extruded polystyrene, RSI.5 (R-3), results in major heat loss from the building shell
- the use of RSI 1.6 (R-9), 51mm (2") sheathing significantly reduces thermal bridging
- switching from batts and steel rafters to loose-fill insulation and wood trusses significantly increases the thermal performance of the attic

- for steel framing, it is better to use less cavity insulation and maximise the amount of insulating sheathing
- temperatures measured at steel stud location were 4°C (8°F) lower than at the cavity for assemblies with 12.5mm (1/2") foam sheathing and 2°C (4°F) lower for assemblies with 51mm (2") foam sheathing.

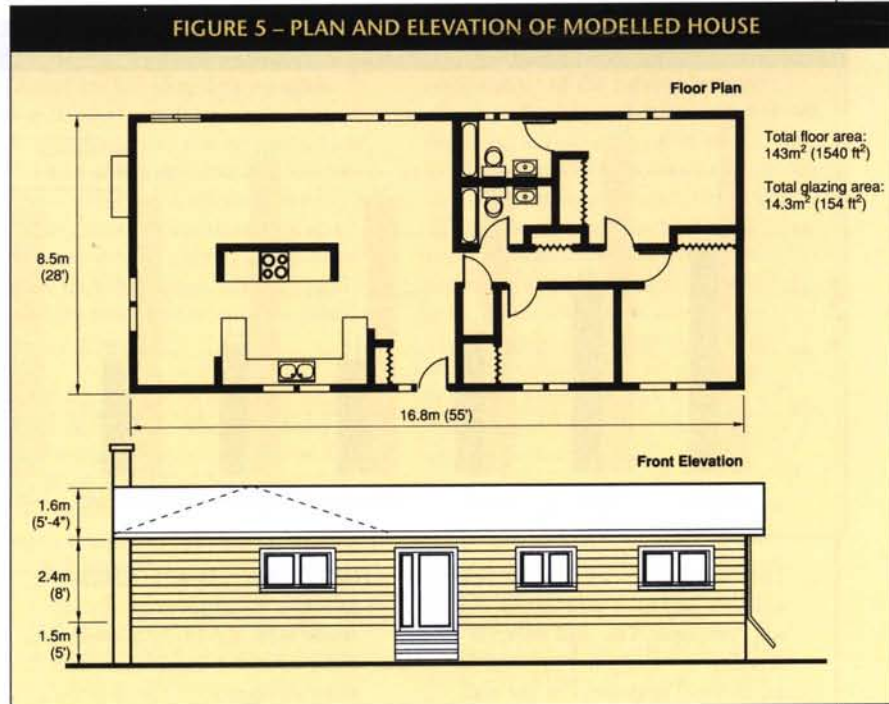
By contrast, researchers at the NAHB noted that for wood framing, the temperature difference between cavities and studs was between 0.5 to 1°C (1 to 2°F).

Thermographic testing done by the Bonneville Power Administration in Portland, Oregon on light gauge steel-frame houses showed walls with plywood sheathing and 18.5mm (.75 in) foam sheathing to be thermally identical.

Infrared thermography of 140mm (6") walls with cavity insulation and RSI 1.1 (R-6) sheathing found interior-wall surface temperatures of 7.3°C (45°F) over steel studs when the outside temperature was 4.4°C (40°F). 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 AISI determined that 12.5mm (1/2") of foam sheathing would keep the temperature difference between the steel stud and the cavity below 1.6°C (3°F). The thermographic field testing of actual houses shows that even with 50mm (2") of foam the temperature difference between the steel stud and the cavity is 2.3°C (4°F). The field performance appears to be significantly worse than the measured laboratory performance.

FIGURE 5 – PLAN AND ELEVATION OF MODELLED HOUSE



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.

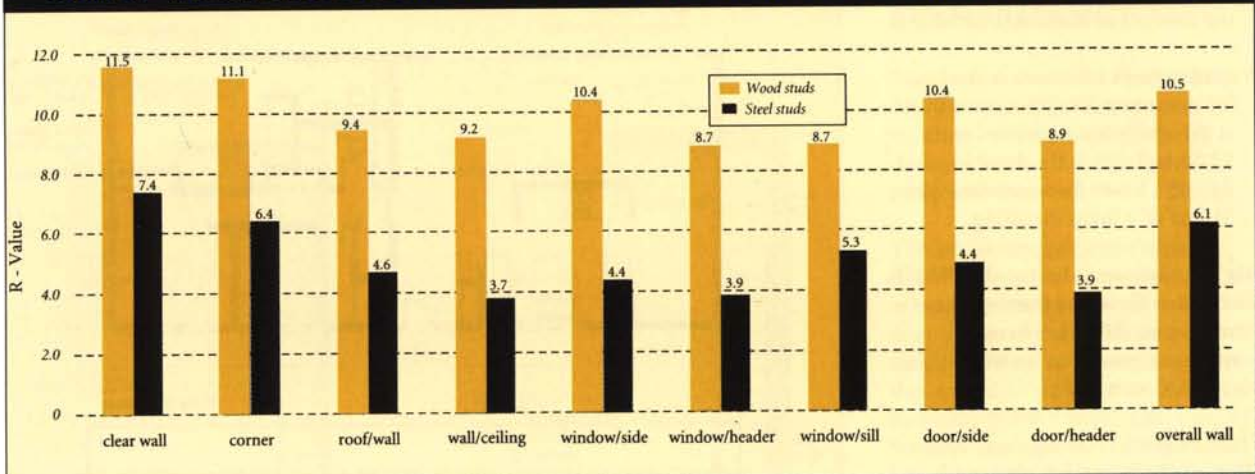
MODELLING OF ENTIRE STRUCTURES

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.

The researchers, Jan Kosny and André Desjarlais, used a computer model, HEATING 7.2, to model the effects of "whole wall" details as well as the effects of various framing and insulation configurations. They modelled the thermal bridges in a 143m² (1540 ft²) single storey ranch house for both wood and steel framing⁴ (Figure 5).



FIGURE 6 – THERMAL RESISTANCES OF WALL COMPONENTS FOR WOOD STUD AND STEEL STUD WALL SYSTEMS



The thermal resistance of the clear wall area and each wall system detail was computed. The wall effective R-value was estimated by combining the thermal resistances of the wall details, subsystems, wall intersections and clear wall area using an area weighted method. The simulation results for the clear wall and overall wall are summarised in Figure 6.

Note that these simulations used 38 x 89mm studs @ 406mm o.c. (2" x 4" studs @ 16" o.c.). The differences between steel and wood framing insulating values are greater for larger cavity depths.

THE STUDY CONCLUDED:

- Effective R-values of clear steel-frame walls are 14-35% lower than those of wood-frame walls with the same configuration for clear walls
- Steel studs reduce the R-value by 47% (18GA, 3.5" @ 16" o.c., no exterior sheathing)
- Wood studs reduce the R-value by 13% (3.5" @ 16" o.c., no exterior sheathing)
- Installing additional sheathing insulation improves the thermal performance of steel-frame walls by increasing the R-value
- Building wall systems are a combination of clear wall areas, wall details and subsystems. They cannot be accurately modelled simply by studying the clear wall area.

- For the wall system reported in this study:

the steel-frame wall effective R-value for the entire wall was 19% lower than clear wall values

the wood-frame wall effective R-value for the entire wall was 9% lower than clear wall values

the steel-frame wall effective R-value was 40% lower than the effective R-value for the wood-frame wall when the entire wall was considered.

In summary, the report concluded that steel-frame walls had lower thermal performance than wood-frame walls for clear-wall laboratory conditions. 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.



INCREASED ENERGY REQUIREMENTS

The obvious effect of using assemblies with poor thermal performance is the requirement for additional energy to heat and cool a building. This increased use of energy translates into an increased cost to the building owner that continues for the life of the building. As energy costs continue to escalate, these costs become more significant.

For example, for the Montreal area (4500 heating-degree days), a small house with 90 m² wall area with 2" x 4" framing and R-13 batts, would use an estimated 2900 kW-h per year more if it was framed with steel than if it was framed with wood.

GHOST MARKS ON 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"⁵ The design of steel studs has not changed, and ghost marking remains a problem.

EFFECTS OF LOW THERMAL PERFORMANCE

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.

In 1940, R.A. Neilson, using equations derived by Albert Einstein, determined that the amount of dust build-up should be proportional to the temperature difference between the wall and the air. Cold surfaces get dirtier faster than warm surfaces.

On a wall with 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 1970's 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 (3.3°F).
- severe discolouration occurred when the temperature at the steel stud was more than 4.5°C (8°F) colder than the cavity.

A 1994 AISI study⁶ found that the temperature of the interior surface of a steel-framed wall with plywood sheathing varied as much as 7.1°C (13°F) between the area over the studs and the area between the studs. When the plywood sheathing was replaced with rigid foam, the temperature variation was reduced to only 1.6°C (3°F) – low enough to prevent ghost mark formation. The report concluded that no ghosting would be expected with foam sheathing of 12.5mm (.5in) or greater thickness.

Thermographic testing of built steel-frame houses indicates that a greater thickness of foam would be required to prevent ghost marks. Testing performed by Steve Andrews of a steel-framed house (Figure 4) showed that, even with 51mm (2") foam sheathing, the temperature difference between the steel studs and the cavity was higher than the 1.8°C (3.3°F) threshold determined by U.S. Steel for prevention of ghost marks.

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. Foam sheathing, 50mm (2") thick, is required to make a steel-framed wall thermally equivalent to a 38 x 140mm (2" x 6") wood-frame wall and eliminate some of the other thermal effects such as ghosting and mould growth. This translates into an increased cost for material only of approximately \$10.00/m² (\$0.97/ft²) of wall area or \$1000 for a 120 m² (1290 ft²) bungalow. There will also be an increased cost for the extra provisions such as extended window and door jambs.

INCREASED ENVIRONMENTAL COSTS

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 CO₂ 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-hr² of energy to manufacture 100m² (1075 ft²) of 25mm (1") rigid foam, or enough to clad a 120m² (1290 ft²) bungalow. The additional environmental costs of the foam must be included when determining the environmental cost of the steel framing because it must be used to achieve the equivalent performance of the wood framing.

The environmental effect of higher energy requirements or the use of foam sheathing is only one aspect of the environmental impact of steel framing. For more information on the environmental impact of steel and wood framing using life cycle analysis, please refer to the Canadian Wood Council's publication "Environmental Effects of Building Materials".

CONCLUSIONS

Energy requirements for buildings are increasingly important, particularly in the harsh climatic conditions experienced in Canada and the northern United States. 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
- 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.

Wood, the only renewable building material, performs well as a structural material and as a thermal barrier resulting in strong, safe and warm buildings.

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