Framing with Steel Versus Wood/ Heat Transfer Issues and Analysis

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This paper compares the thermal performance of steel and wood-framed systems. It illustrates the impact of steel framing on building's annual energy use, presents results of finite difference heat transfer analysis for wood and steel-framed assemblies, discusses the thermal characteristics of steel and wood-framed systems and discusses possible improvements to make steel framing more energy efficient.

The comparison showed that the commonly practiced method of replacing wood with steel stick-for-stick results in a 32 percent increase in heating and cooling energy consumption of a typical house in California Climate Zone 12. Two-dimensional finite difference analysis showed that a highly conductive material such as steel not only creates a thermal bridge in the cavity, but also causes lateral flow in the layers adjacent to the framing. The combined effects of thermal bridging and lateral flow in the assembly layers reduce the overall R-value considerably. The magnitude of the lateral flow depends on the thermal conductivity of the assembly layers, especially the layers directly attached to the framing. A conductive layer increases the lateral flow while an insulative layer reduces it.

An insulative layer can mitigate the thermal bridging and lateral heat flow by interrupting the path and the direction of flow. An insulative layer in a wood-framed system is less effective because wood framing is less conductive than steel. Other techniques investigated for reducing thermal bridging are: increasing stud spacing, and removing parts of the web, if structurally feasible.

INTRODUCTION

Finite difference analyses and guarded hot box tests have shown that steel-framed systems that are designed using the traditional wood framing techniques are about 50 percent less efficient than their wood-framed counterpart. Having to comply with building energy efficiency standards that are based on wood frame construction, designers of steel-framed systems are faced with the challenge of designing systems that are energy efficient enough to meet or exceed the thermal performance of traditional wood-framed systems.

Historically, replacing wood with steel stick-for-stick has been a common practice in steel-framed construction. This type of steel framing design can result in a significant increase in heating and cooling costs of a building. The magnitude of the increase depends on the severity of the climate. DOE-2.1E (Hirsch 1994) models have shown that a typical wood-framed residential building in California Climate Zone 12—Sacramento, California—with 2,775 heating degree days and 10,464 cooling degree hours has an annual heating and cooling energy consumption of 45.7 kBtu/ft^2. Using steel for framing would increase the annual consumption by 14.4 kBtu/ft^2 (32 percent) to 60.1 kBtu/ft^2. These values are the source energy with a multiplier of three for electricity and a multiplier of one for gas. The modeling assumptions are listed in Table 1.

The steel framing that penetrates the cavity insulation reduces the thermal efficiency of the insulation. As will be seen in this paper, steel framing, being a better conductor of heat than wood, not only reduces effectiveness of the cavity insulation, but also increases lateral heat flow which further reduces the effectiveness of the insulation.

Hand calculation techniques such as American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. (ASHRAE) parallel path for wood-framed systems and the zone method for steel-framed systems used for conventional frame designs produce similar results for most assemblies when compared with results from finite difference models and guarded hot box tests. However, these hand calculation procedures use simplifying assumptions, which limit the ability to study the characteristics of framed systems and to calculate the improvements achieved by implementing alternative design techniques. This study uses finite difference analysis technique to evaluate heat transfer issues related to the effect of framing on the systems thermal performance especially when the assembly contains highly insulative and highly conductive materials.

Heat Transfer Analysis

Steady-State vs. Unsteady-State. The ability of a building envelope assembly to resist the flow of heat depends on

Table 1. Modeling Assumptions for Comparing Wood and Steel-Framed Buildings

Building Feature	Assumption
Conditioned floor area	1761 ft^2
Number of stories	2
Floor	Slab-on-grade, no edge insulation
Wall	R-19, 16″ frame spacing, 25% framing
Ceiling	R-38, 24″ frame spacing, 7% framing
Total window area	282 ft^2, equally distributed in all four directions
Window U-value	0.65
Heating system	Gas central furnace, AFUE = 78 percent
Cooling system	Central air conditioner, split system, SEER = 10
Water heating	None
Duct losses	None

the overall resistance R-value and the thermal mass of the assembly. Overall resistance is a thermal property that is calculated using steady-state analysis. However, accounting for the thermal mass, which stores and releases thermal energy causing delay in the flow of heat, requires performing unsteady-state analysis (time-varying air temperature).

To illustrate the effect of the thermal mass on the heating and cooling energy consumption of a building, both wood and steel-framed buildings in the above example were modeled without the mass effect (modeled as U-values only) using DOE-2.1E. The results showed that the annual heating and cooling energy increased by 5.5 kBtu/ft^2 for the wood-framed building and by 4.6 kBtu/ft^2 for the steel-framed building. This represents a difference of less than 1.0 kBtu/ft^2 per year between the wood and steel-framed buildings. This example illustrates that although the mass effect may be significant for calculating the heating and cooling energy consumption of a building, it has little effect on the relative thermal performance of steel and wood-framed systems and that the mass effect of steel framing can be assumed to be comparable to that of wood framing. Not having to account for the thermal mass substantially simplifies the analysis by allowing steady-state analysis to be used to calculate overall resistance R-values, to study the effect of framing in the flow of heat, and to study the thermal interaction between framing and the construction materials in the assembly.

Modeling Approach and Assumptions. Typical building envelope assemblies include thermal anomalies due to window and door frames, wall corners, and floor and ceiling connections to the wall system. Available resources, limited the scope of this study to two-dimensional analysis of the flat portion of framed assemblies that include some window and door framing and tracks. Thermal analysis of wall corners and wall connections to floor and ceiling should use a three dimensional model and is not included in this analysis.

The thermal analysis was performed using FRAME version 2.1 finite difference program (FRAME 1991). FRAME is a two-dimensional finite difference program for steady-state heat transfer analysis of window frame systems. This program can also be used for modeling and analyzing framed envelope assemblies. To validate the FRAME program and the modeling technique, three cases from the tests performed and published by the American Iron and Steel Institute (Barbour et al. 1994) were modeled using the FRAME program and the results were compared. The first case consisted of 3 ⅝″ by 1 ⅝″ framing, R-11 batt, ½″ plywood and ½″ gypsum board. The second case consisted of 3 ⅝″ by 1 ⅝″ framing, R-11 batt, 1″ insulative sheathing (rigid insulation) and ½″ gypsum board. The third case consisted of 6″ by 1 ⅝″ framing, R-19 batt, 48″ stud spacing, ⅞″ horizontal furring at 24″ on center on both sides, ½″ gypsum board and ½″ plywood. The overall R-values calculated using finite difference models were nine percent lower than the test result for case one, two percent lower than the test result for case two, and seven percent higher than the test result for case three. Considering that the precision of the guarded hot box method is approximately 8 percent (Barbour et al. 1994), the FRAME program's calculated overall R-values are within the accuracy of the test results.

After validating the FRAME program and the modeling technique, several models were developed to calculate the overall R-values of wood and steel-framed systems, study heat flow through these systems and investigate ways for improving the thermal efficiency of steel-framed system. These models did not include the effects of fasteners. The construction layers used were stucco with thermal conductivity of 5.0 Btu-in/hr-ft^2-°F, plywood with thermal conductivity of 0.80 Btu-in/hr-ft^2-°F, steel sheathing with thermal conductivity of 314.0 Btu-in/hr-ft^2-°F, insulative sheathing with R-4.00 per inch and R-8.00 per inch, insulative sheathing with theoretical values of R-50 per inch, and R-65 per inch, gypsum board with thermal conductivity of 1.11 Btu-in/hr-ft^2-°F, and air space. The FRAME program could not model convective and radiative heat transfer of the air space; rather, it calculated an effective thermal conductivity which accounted for those mechanisms. The FRAME program calculated the effective thermal conductivity for the air space based on emmitance of 1.00 and a temperature difference of 5 degrees across the air space. These parameters resulted in an effective conductivity of 1.09 Btu-in/hr-ft^2-°F for the air space with one-inch metal furring which agreed well with the published test results.

The output from the FRAME program included the heat flow plot and the total heat flux when the interior and exterior air temperatures were maintained at 70° F and 45° F respectively. Wind speed of 15 MPH was assumed for the exterior side.

The analysis was limited to two-by-four framing systems. The actual framing dimensions were 3 ½″ by 1 ½″ for both wood and steel framing members. The steel framing thickness was 0.048″ that corresponds to 18-gauge steel. Thermal conductivities of steel and wood framing members were 314 and 1.0 Btu-in/hr-ft^2-°F respectively.

The ‘‘framing percentage’’ is the ratio of the framing width for wood or flange width for steel to the spacing between studs. In a two-by-four stud construction at 16 inches on center, framing is about 9 percent of the assembly surface. The 1993 edition of ASHRAE Handbook of Fundamentals estimates the overall percentage of wall framing including multiple studs, plates, sills, and extra framing around doors and windows to be 25 percent.

Because modeling an entire wall system would not be practical, a thermally equivalent section of the wall was modeled for this study. The modeled section consisted of a framing member in the wall assembly that is one foot high, measured along the framing member, and a width equal to a theoretical spacing between framing members that would achieve the ASHRAE overall framing percentage. Twenty five percent framing resulted in a theoretical spacing between wall studs of 6.0 inches. The additional framing assumed in the model did not account for the wall corners and floor and ceiling connections with the wall. These areas typically have high concentrations of framing which result in significant loss of heat from the building especially when steel framing is used. Modeling these areas will be the focus of future studies.

RESULTS

The results of the finite difference analysis are presented in the form of heat flow plots and overall R-values. The overall R-values were calculated using the total heat flow calculated by the FRAME program, the area of the section of the assembly that was modeled and the temperature difference between the cold and the warm sides. The mathematical formulation for calculating the heat flow is as follows:

$$Q = (A / R) \times (T_{warm} - T_{cold})$$

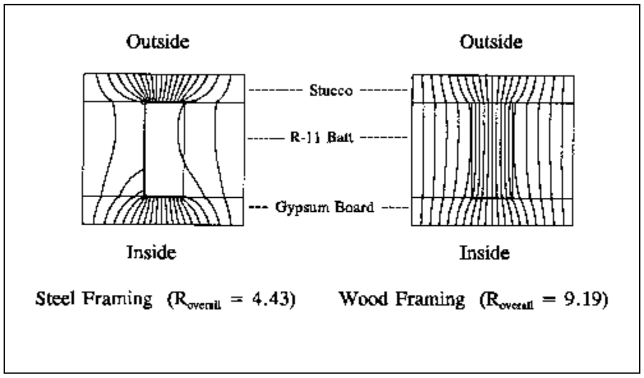
where Q is the total heat flow in Btu/ hr-ft^2-°F
A is the area of the section of the assembly that is modeled in ft^2
R is the assembly’s overall R-value in hr-ft^2-°F/Btu
T_{warm} is the warm side temperature in degrees Fahrenheit
and T_{cold} is the cold side temperature in degrees Fahrenheit

Re-arranging the formula to solve for the overall R-value:

$$R = (A / Q) \times (T_{warm} - T_{cold})$$

Figure 1 shows overall R-values and paths of heat flow through standard wood and steel-framed assemblies. Standard assemblies consist of framing at 16 inches on center, R-11 cavity insulation, 25 percent framing, one-inch gypsum board on the interior side, and one-inch stucco on the exterior side. Note that the wall layers are modeled as being one inch thick for clarity of graphical output of the FRAME program. The calculated overall R-value is 9.19 hr-ft^2-°F/Btu for the wood-framed assembly and 4.43 hr-ft^2-°F/Btu for the steel-framed assembly. The standard wood-framed assembly’s overall R-value is more than two times higher than that of the standard steel-framed assembly. Figure 1 shows that more heat flows through framing. That is seen as higher concentration of heat flow lines in the framing than in the rest of the assembly. The concentration is higher in steel framing than in wood framing indicative of higher conductivity of steel. Figure 1 also shows that the heat flow entering and leaving the steel framing has a larger lateral component than heat flow entering and leaving the wood

Figure 1. *Comparing Standard Wood and Steel-Framed Assemblies*



framing. The lateral flow causes the heat flow lines to diverge, increasing the portion of the assembly that is thermally affected by the framing and lowering the overall R-value. Higher conductivity of steel framing and large lateral flow that it creates in the assembly layers are reasons for lower overall R-value of steel-framed systems.

Thermal performance of steel-framed systems can be improved by interrupting the flow of heat entering and leaving steel framing and reducing the lateral flow component. The flow of heat can be interrupted by methods such as: (1) increasing the frame spacing; (2) removing part of the web by punching holes in it; and (3) using insulative sheathing as an exterior layer. This will also reduce condensation in the cavity.

Increasing the spacing to 48 inches with one inch of air space separating stucco from the framing due to one-inch furring increases the overall R-value to 7.66 hr-ft^2-°F/Btu. This is 1.7 times higher than the overall R-value of the standard steel-framed construction, approaching the performance of the standard wood-framed system.

Removing 75 percent of the web measured along the length of the stud (75 percent knock-out), increases the overall R-value to 6.31 hr-ft^2-°F/Btu. This is 1.4 times higher than the overall R-value of the standard steel-framed construction. Having knock-outs in the web does not weaken the structural strength of the stud significantly as most of the structural strength of a stud is due to its flanges. However, calculations must be performed to ensure the structural integrity of the framing system. For simplicity, the web with knock-outs was modeled as a solid web with smaller thickness proportional to the reduction in the web area. Finite difference models of wall cross-sections through the web with varying knock-out sizes showed that as the knock-out size and hence the distance that heat travels to bypass the knock-out increases, the overall R-value increases. Although the distance that heat travels increases proportionally to the knock-out size, the overall R-value does not change significantly until the knock-out interrupts more than half of the heat flow area of the web. This illustrates that the increase in the overall R-value is mostly due to the reduction in the web area and not the increase in the distance that the heat has to travel around the knock-outs.

The above two methods are effective in reducing the heat flow through the framing but do not affect the lateral heat flow in the layers.

An insulative sheathing layer—also referred to as rigid insulation in this paper—with R-value of 4.00 hr-ft^2-°F/Btu installed between framing and stucco in the standard steel-framed system interrupts the flow of heat and reduces the lateral flow, resulting in an increase of the overall R-value to 9.62 hr-ft^2-°F/Btu. This is 5.19 hr-ft^2-°F/Btu more or 2.2 times higher than the overall R-value of the standard steel-framed system and slightly higher than the overall R-value of the standard wood-framed system. The insulative sheathing adds R-1.19 in addition to its R-4.00 insulative value to the standard steel-framed system. The insulation layer not only interrupts the flow of heat through steel framing but also reduces the lateral heat flow, further increasing the overall R-value by 1.19 hr-ft^2-°F/Btu. Installing R-4.00 rigid insulation would increase the overall R-value of the standard wood-framed system by 4.25 hr-ft^2-°F/Btu, only 0.25 hr-ft^2-°F/Btu more than the insulation's insulative R-value. The rigid insulation is less effective in wood-framed systems because the lateral flow is smaller than in steel-framed systems. Figure 2 shows the heat flow through steel and wood-framed systems with R-4.00 rigid insulation.

Increasing the insulative value of the sheathing to R-8.00 further reduces the lateral heat flow as illustrated in Figure 3. Note that with the reduction in the lateral flow after

Figure 2. *Comparing Standard Wood and Steel-Framed Assemblies When Using R-4 Rigid Insulation*

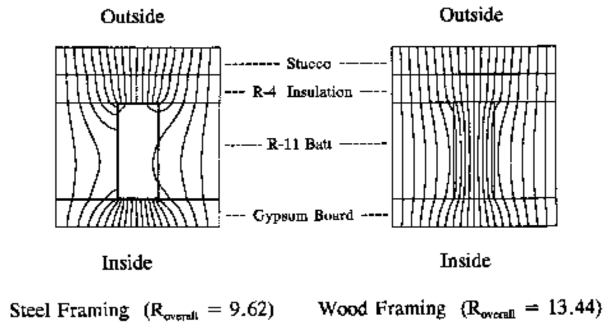
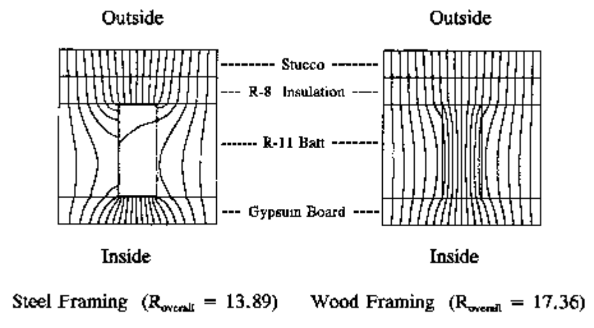


Figure 3. *Comparing Standard Wood and Steel-Framed Assemblies When Using R-8 Rigid Insulation*



increasing the sheathing R-value from 4.00 hr-ft^2-°F/Btu to 8.00 hr-ft^2-°F/Btu, the difference in overall R-values between wood and steel-framed systems drops from 3.82 hr-ft^2-°F/Btu to 3.47 hr-ft^2-°F/Btu. Going one step further, in a hypothetical situation where R-50 is installed, the difference in overall R-values further decreases to 2.70 hr-ft^2-°F/Btu as shown in Figure 4. As the insulative value of the sheathing approaches 65 hr-ft^2-°F/Btu, the overall R-values of steel and wood-framed systems become identical. Using R-65 exterior insulation would result in identical overall R-values of 73.53 hr-ft^2-°F/Btu for both wood and steel-framed systems.

Some steel frame designers use strips of steel to provide shear support for the assembly. Installing strips of steel increases the lateral component of heat flow. A 1/16-inch layer of steel with R-0.0003 installed between framing and stucco in the standard steel-framed system results in a decrease in the system's overall R-value to 4.20 hr-ft^2-°F/Btu. This is 0.23 hr-ft^2-°F/Btu less than the R-value of the standard steel-framed system. On the other hand, installing 1/16-inch layer of steel in a wood-framed system reduces the system's overall R-value by only 0.07 hr-ft^2-°F/Btu to 9.12 hr-ft^2-°F/Btu.

Because the steel layer is thin, it is not possible to graphically show the heat flow through it. But, modeling a one-inch layer of steel between stucco and framing showed that the overall R-value of the steel-framed assembly becomes 4.14 hr-ft^2-°F/Btu and the overall R-value of the wood-framed system becomes 9.12 hr-ft^2-°F/Btu. The small difference between the overall R-values with 1/16-inch and one-inch layers of steel in the steel-framed system and no difference in the wood-framed system illustrate that the heat flow path through the steel layer is nearly independent from the thickness of the steel layer. Figure 5 shows the heat flow lines and the overall R-values of steel and wood-framed assemblies with one-inch layer of steel installed between stucco and the framing.

Figure 4. *Comparing Standard Wood and Steel-Framed Assemblies When Using R-50 Rigid Insulation*

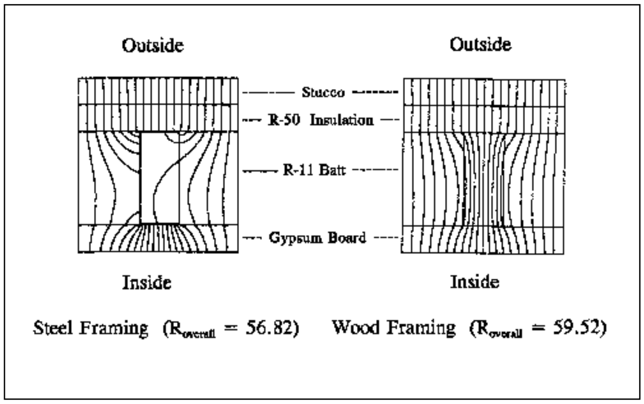


Figure 5. *Comparing Standard Wood and Steel-Framed Assemblies When Using a Layer of Steel*

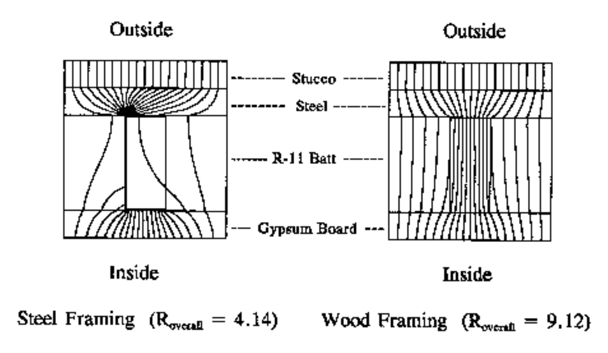
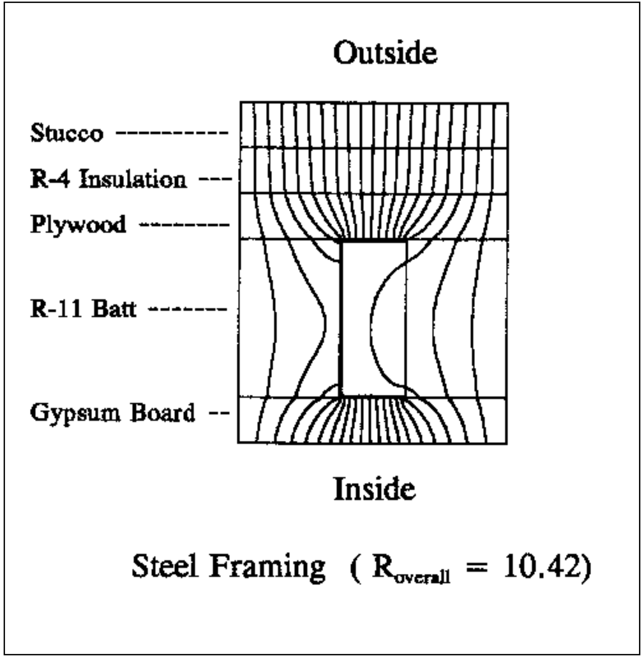


Figure 6 shows that if plywood, R-4.00 rigid insulation and stucco are installed with plywood directly attached to steel framing and the rigid insulation between plywood and stucco, the overall R-value becomes 10.42 hr-ft^2-°F/Btu. Reversing the locations of the rigid insulation and plywood with the rigid insulation adjacent to the steel framing would increase the overall R-value by 1.04 times to 10.87 hr-ft^2-°F/Btu (Figure 7). The closer the insulative sheathing is to the framing, the less lateral flow is created in the assembly,

Figure 6. *Standard Steel-Framed Assembly with Plywood Attached to Framing*



making the insulative sheathing more effective. This can be seen by comparing Figures 6 and 7.

In the above case, if R-8.00 rigid insulation is used instead of R-4.00, the assembly's overall R-value when the rigid insulation is attached to framing becomes 1.05 times higher than when the plywood layer is attached to the framing.

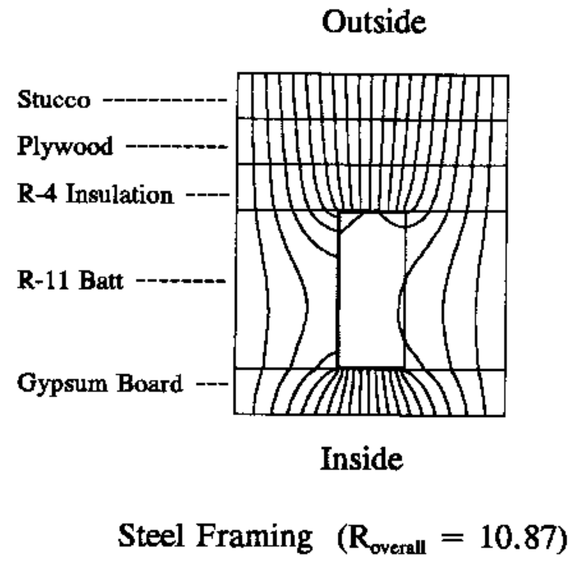
The benefit of attaching the rigid insulation to the framing becomes greater when a conductive material such as a layer of steel is used instead of plywood in the above case. With R-4.00 rigid insulation directly attached to the framing and steel and stucco as the second and third layers, the overall R-value becomes nearly 1.2 times better than the overall R-value for the case where the steel layer is attached to the framing and rigid insulation and stucco are the second and third layers.

CONCLUSIONS

Loss of thermal efficiency in steel-framed systems is caused by high thermal conductivity of steel framing and the lateral heat flow in the layer adjacent to the framing. The magnitude of the lateral flow increases as the thermal conductivity of the layer adjacent to the framing increases.

The overall R-value of the standard steel-framed system discussed in the previous section was 4.43 hr-ft^2-°F/Btu. Adding R-4 rigid insulation between stucco and steel framing increased the overall R-value by 5.19 hr-ft^2-°F/Btu, 1.19 hr-ft^2-°F/Btu above and beyond the insulative R-value of the installed rigid insulation while adding a layer of steel reduced the overall R-value by 0.23 hr-ft^2-°F/Btu. In wood framing, adding R-4 rigid insulation increased the assembly's R-value by 0.25 hr-ft^2-°F/Btu above and beyond the insulative value of the rigid insulation and adding a layer of steel reduced the overall R-value by only 0.07 hr-ft^2-°F/Btu. Insulative sheathing is more effective when installed in a steel-framed system because of the larger lateral flow that occurs in these systems. Higher lateral flow in steel-framed systems also causes greater reduction in the overall R-value when a layer of steel is used.

Figure 7. *Standard Steel-Framed Assembly with Rigid Insulation Attached to Framing*



This paper investigated three different techniques for improving the thermal efficiency of steel-framed systems with the following conclusions:

(1) Reducing the web area increases the overall assembly's R-value. For example, by removing 75 percent of the web in the standard steel-framed system, the overall R-value increases by 1.4 times.

(2) Increasing spacing between framing members to 48 inches increases the overall R-value of standard steel-framed system by 1.7 times.

(3) Using insulative sheathing placed adjacent to the framing increases the overall R-value of the assembly. For example using R-4 rigid insulation in the standard steel-framed system increases the overall R-value by nearly 2.2 times.

Designers can use these three techniques individually or in any combination to improve the performance of steel-framed systems to meet or exceed the thermal performance of traditional wood-framed systems.

Installing rigid insulation is the most effective method of improving the thermal performance of steel-framed systems because it interrupts the flow of heat and reduces the lateral flow. Rigid insulation is more effective when installed in a steel-framed assembly compared to a wood-framed assembly. And the thermal characteristics of wood and steel-framed systems become closer as the R-value of the rigid insulation increases.

The location of the insulative sheathing in a steel-framed system is important. Rigid insulation is most effective when it is installed against the framing. The analysis indicate that, for maximum thermal efficiency, the most insulative layer must be installed closest to the framing and the most conductive layer must be installed as far away from the framing as possible.

Energy efficient wall, roof and floor systems do not ensure energy efficiency of the overall building envelope. Wall framing for windows and doors, building edges and corners where walls meet, and the roof and floor connections to walls have high concentrations of framing that are not fully accounted for in this two-dimensional analysis. Substantial heat transfer takes place through these areas of high steel concentration, especially when highly conductive steel framing is used. Framing systems are sometimes over-designed for higher structural strength than is required. Conventional two dimensional calculation methods do not account for thermal efficiency of wall, floor and roof intersections, or wall framing for doors and windows. Three dimensional finite element analysis is needed to address these issues.

This analysis also does not account for the difference in infiltration between wood and steel-framed systems. There is some indication (Minch & Marston 1995) that conventional steel frame construction may result in higher infiltration than conventional wood frame construction because the web knock-outs allow for less restrictive air movement through the assembly. Both infiltration and edge effects should be addressed in future analysis of steel-framed systems.

The techniques for improving the performance of steel framing are not limited to those considered in this paper. There may be other approaches to the use of steel framing that could result in improvements in the performance of steel-framed systems. In some cases, ASHRAE's zone method may be used to calculate the overall R-value. However, as mentioned before, the simplifying assumptions in the hand calculation techniques may result in under- or over-estimation of the improvement. Laboratory testing, finite difference or finite element analysis may have to be used for more accurate calculation of the overall R-values for steel-framed systems.

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