EFFECTS OF FRAMING ON THE THERMAL PERFORMANCE OF WOOD AND STEEL-FRAMED WALLS

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ABSTRACT

The term “framing factor” is widely used to express a percent of the total wall area occupied by framing members. The framing factor for hot-box tests is often between 11 and 14%. In reality, however, the framing factor is often much larger. According to a 2002 Report framing factors up to 27% can be found in residential walls in California in 2001. A similar study performed by ASHRAE in 2003 found an average 25% framing factor for US homes.

This paper reports, experimental work and numerical analysis of the thermal performance of various configurations of structural components in wood and steel-framed walls. In addition, the consequences of installation imperfections in cavity insulation on thermal performance are analyzed. The results of the study demonstrated significant sensitivity in some configurations of residential walls to the framing factor and insulation installation imperfections.

Keywords

R-value, Framing Factor, Cavity Insulation, Framing Effect Coefficient, Steel Frame walls, Wood-frame walls

TERMINOLOGY OF THE WHOLE WALL R-VALUE PROCEDURE USED IN THIS PAPER

The following list of thermal performance terms was introduced in 1994 [1]. The “Whole Wall Procedure” has been proposed for estimating the whole opaque wall R-value (whole-wall R-value), independent of system type and construction materials.

Center-of-Cavity R-value

Sum of wall material R-values calculated at a point in the center of a wall cavity. This R-value doesn’t include framing materials.

Clear wall R-value

R-value for the wall area containing only insulation and necessary framing materials for a region with no windows, corners, or connections between other envelope elements such as roofs, foundations, and walls.

Framing Factor

Framing factor is the ratio of the area of all structural members (studs and top and bottom plates or tracks in case of steel framing) to the total wall area.

Interface details

A set of common structural connections between the exterior wall and other envelope components, such as wall/wall (corners), wall /roof, wall/floor, window header, window sill, door jam, door header, and window jamb, that make up a representative residential wall.

Whole-wall R-value

R-value estimation for the whole opaque wall including the thermal performance of the "clear wall" area with insulation and structural elements and typical envelope interface details, including wall/wall (corners), wall /roof, wall/floor, wall/door, and wall/window connections.

TECHNICAL BACKGROUND

In keeping with the Enermodal Engineering report for the California Energy Commission, all wall assemblies in this report have framing factors of approximately 27% [2, 3]. It is well known that a presence of framing members (like wood or steel profiles) reduces the R-value of a wall system. The measure of this effect is known as the framing effect coefficient '*f*' of a wall, which is calculated using the following simple expression that contains clear-wall R-value, $R_{cw,}$ and the center-of-cavity R-value, R_n .

$$f = \left[1 - \frac{R_{cw}}{R_n}\right] * 100 \tag{1}$$

The US residential construction market is dominated by wood-frame construction. Light-gage steel framing, however, is gaining some interest; especially after years like 2005 with several hurricanes devastating our coastal areas. It is not difficult to understand that over 90% of the debris from a hurricane is damaged wood framing, which generates tremendous disposal problems in areas of high termite activity. On the other hand, steel framing offers many advantages like termite resistance, dimensional stability, and lightweight construction, which can be recycled. The main disadvantage is the high heat conduction of steel. According to the American Iron and Steel Institute, steel-framed home construction has increased by 300% in the US and Canada since 1998. [4]

Clear wall R-value [1] is the most widely-used thermal performance measure of wall assemblies. Clear-wall R-value can be measured using a guarded hot box. [5] An example of a test wall assembly containing nominal 2 x 4 inch framing installed 16 in. OC is shown in Figure 1.

ASHRAE 90.1 and 90.2, the International Energy Conservation Code (IECC), and Title 24 of the California Energy Commission (CEC) contain the insulation standards for buildings [6, 7, 8, 9]. For thermal calculations, the ASHRAE Handbook of Fundamentals [10] recommends using the parallel-path method for wood framing and modified-zone method for steel-frame walls [11]. CEC Title 24 thermal requirements for steel-frame wall assemblies are based on the zone method [9,11]. IECC standard requirements are based mostly on results of ASHRAE or DOE research projects. However, they are very often modified based on requests from companies producing different building materials, consulting companies, or trade associations. The common denominator for all prescriptive thermal requirements coming from ASHRAE, IECC, and CEC, is the fact that they all recognize only stud material, stud spacing, and stud depth. That is why, from a practical perspective, it is very common that, in R-value or U-value calculations top and bottom plates are neglected. This leads to unrealistically low framing factors (9.4% for stud spacing 16-in. OC and 6.3% for stud spacing 24-in. OC). In hot-box tests, the top and bottom plates (or tracks in case of steel framing) are usually parts of the test specimens, which yields framing factors of 14 % for stud spacing 16-in. OC and 11% for stud spacing 24-in. OC.

In 2001 and 2003, CEC and ASHRAE projects estimated the framing factor in current low-rise residential buildings [3,12]. It was found that in Californian low-rise residential buildings approximately 27% of the total wall area is occupied by framing and the average framing factor in walls nationwide is approximately 25%. This number includes the framing used around windows and doors, structural reinforcement, corners framing, etc. In case of wood framing, this fact means that, for example in California, 27% of the opaque wall area is made of solid wood.

For wood-stud walls without foam-sheathing the authors propose the following method of evaluating a potential magnitude of R-value differences in cases where different framing factors are considered. This method permits a quick estimation of the whole-wall R-value from the center-of-cavity R-value and the framing factor.

> **Wood framing** – each percent of wall framing reduces nominal center-of-cavity R-value by one percent (**example**: *in-series R-value for ½-in. of gypsum board, R-13 fiberglass batts, and ½-in. OSB board is R-14. Assuming 25% of framing we have R-3.5 reduction of the nominal R-value. This yields wall R-value of about R-10.5)*

Some R-value calculations and percent-differences from the basic cases (with only studs included in the calculation), are presented in Table 1 for wood-stud walls with ½-inch gypsum on one side and ½-in. OSB on the second side and R 13 cavity insulation.. It can be seen that R-value difference between wall configurations currently used for hot-box testing (14% of framing) and walls containing 25% of framing is close to 15%. This fact leads to the conclusion that the framing factor for a hot-box test should reflect current construction practice. For steel-framed assemblies, due to more complex character of heat transfer, such simplified calculations are not possible. However, similar differences in R-values may easily exceed 30% for different levels of framing.

TABLE 1. R-values for Nominal 2x4 in. Wood-Frame Walls

In-Series R-14	**Only studs included (basic)**		**Studs and plates included**			**25% framing factor**		
Stud spacing:	Framing factor	**R-value h·ft^2·°F/BTU**	Framing factor	**R-value h·ft^2·°F/BTU**	% difference	Framing factor	**R-value h·ft^2·°F/BTU**	% difference
16-in.	9.4%	**12.7**	14.1%	**12.0**	5.2%	25.0%	**10.5**	17.2%
24-in.	5.2%	**13.3**	11.0%	**12.5**	6.1%	25.0%	**10.5**	20.9%

A DOE-2.1 whole-building energy modeling exercise was performed to demonstrate a magnitude of potential differences in heating and cooling loads' calculations performed for a 1500 ft^2 one-story house located in Atlanta, GA or Minneapolis, MN. For each location, two options for wall R-values were considered ; R-12.7 h·ft^2·°F/BTU and R-10.5 h·ft^2·°F/BTU. For the house located in Atlanta, the wall R-value difference between R-12.7 h·ft^2·°F/BTU and R-10.5 h·ft^2·°F/BTU yielded in DOE 2.1E simulations about 17% difference in annual heating loads generated by walls and similarly about 18% difference in cooling loads. For Minneapolis, MN, the annual heating loads generated by walls were 15% different and about 18% difference in cooling loads was observed.

The Residential Energy Services Network (RESNET), which is widely-used for designing and code-approval purposes, does not address the intense thermal bridging generated by architectural and structural components with increased amount of framing members as well as insulation imperfections [13]. Building load calculation programs like Manual J [14] also does not incorporate these thermal anomalies. Previous ORNL research demonstrated that about 10% to 15% of the US residential energy consumption (about 0.8 Quad a year) is not normally included in building loads analysis, sizing HVAC equipment, and whole building energy consumption calculations [15,16]. In this paper, this theoretical gap in load analysis and in some standard requirements for thermal calculations and R-value testing is addressed for most common wood and steel-framed wall technologies.

Quality of construction and insulation installation plays important role as well. It is well known that, poorly installed cavity insulation can significantly impair the thermal performance of building envelope components. One of the most common problems in residential construction industry is precision of the installation of structural members. It is very common to find studs offset by ± 1 inch, or locations where some structural members are misplaced, twisted, or buckled under structural, moisture, and thermal loads. These imperfections are not important for loose-fill or spray-applied insulations. They represent a significant challenge for building envelopes insulated with factory-made batts, which are a dominant product in the US residential market. For 16-in. o.c. wood framing, factory-made batts are available in regular widths of 14 1/2 in and for steel framing oversized batts of 16 in. width are produced. Similarly for a 24 in. o.c. assemblies, 22-1/2-in regular size and 24-in. oversized batts are available. For locations with different than nominal stud spacing, batts have to be precut to the size of the wall cavity. In field conditions, this work is not always precise. That is why, it is very common to find either un-insulated air pockets or compressed insulation batts. It is important to know that insulation material industry is trying to overcome these problems by introduction of additional no-standard batt sizes and different installation strategies.

The main purpose of this work is to validate the above speculations, and when found defendable, to incorporate them into the whole- building energy calculations and maybe…, initiate some changes in existing code requirements/recommendations for R-value or U-value calculations and hot-box testing. In order to achieve this goal, representative geometries for wood and steel-framed walls need to be defined to reflect existing construction practices. In this work, with the help of 3-D finite difference modeling, the thermal effects of various configurations of structural components in wood and steel framed walls with 27% framing factor were analyzed. In addition, wall assembly with 24% framing factors was designed for hot-box testing and a series of hot-box measurements were performed on wood and steel-framed walls.

HOT_BOX TESTING OF WALL ASSEMBLIES WITH 24% FRAMING FACTOR

. Three configurations of nominal 2x4 inch wood and steel-framed walls insulated with R-13 $h\cdot ft^2\cdot{}^oF/BTU$ (3.5-in. thick) fiberglass batts were tested in the ORNL guarded hot box in accordance with ASTM C 1363. In these walls, nominal 2x4 inch wood or steel studs were constructed 16-in. OC. The framing factors for all these wall assemblies were slightly greater than 24%. During all three hot box tests, temperature differences across the test specimen walls were between 40 to 45 ºF with the mean temperatures close to 74 ºF.

FUGURE 1. Steel Stud Wall Assembly with 24 % Framing Factor

As shown on Figure 1, in the hot-box tests the top and bottom plates were included into the test specimens. R 13 fiberglass batts were carefully cut to fill wall cavities without compression. Wall surfaces were finished with ½-in. thick gypsum boards and OSB sheathing. The first test wall was constructed with nominal 2x4 in. wood studs. In the second and third walls standard C-shape 3.5 in. 16-ga. light-gage steel framing was used. The third wall was similar to the second wall with the addition of a ¾-in. thick expanded polystyrene foam sheathing. Test results are summarized in Table 2.

TABLE 2. Hot-box Test Results for Wood and Steel-framed Wall Assemblies with Studs 16-in. OC

Wall configuration:	Wood stud wall Base 16-in.	Steel stud wall Base 16-in.	Steel stud wall ¾-in. XPS
Air temperature of the metering box [ºF]	100.1	100.0	100.0

Air temperature of the climate side [ºF]	50.1	50.0	50.0
Temperature difference	45.5	43.1	45.4
T(mean) [ºF]	74.3	73.6	74.1
Clear wall R [h·ft^2·ºF/BTU] (measured)	**9.65**	**5.78**	**9.37**
Center-of-Cavity R-value [h·ft^2·ºF/BTU]	13.95	13.95	17.95
%-difference in R-values	**30.8%**	**58.6%**	**47.8%**

As shown in Table 2, nominal center-of-cavity R-values are significantly greater than the clear-wall measured R-values or the calculated clear-wall R-values. The first and second walls had the same center-of-cavity material R-values. The hot-box clear-wall R-value results, however, were 40 to 70% of the center-of-cavity R-values. This measurement is an example that shows that center-of-cavity R-values are a poor choice for code approvals, load calculations, or whole-building energy simulations. In addition, this series of hot-box tests showed that the addition of a ¾-in. thick XPS foam sheathing to steel-frame walls doesn't contribute enough thermal resistance to match the thermal performance of the 2x4 in. wood-frame walls insulated with the same type of R 13 batt insulation.

THERMAL ANALYSIS

In this work, various configurations of 2x4 wood or steel-frame walls were analyzed numerically for clear-wall R-value. The finite difference code, Heating 7.3, was used for this thermal analysis. [17] This code was calibrated over a number of standard wood and steel-framed wall systems and its accuracy is well documented. [1, 15, 18]. In addition, the computer model was validated with the hot-box test results for the steel stud wall that were part of this project. Three-dimensional computer simulations were within 5% of the thermal measurements.

With the use of the calibrated computer model, each wall configuration was analyzed for steady-state heat transfer in three-dimensions. Clear-wall R-values were calculated for the different wall configurations from calculated heat fluxes through the systems.

WALL CONFIGURATIONS USED FOR THERMAL ANALYSIS

A hot-box facility operated in accordance with ASTM C1363 [5] with test specimens 8 by 8 ft. was used to measure wall heat flues. Tests with wall framing installed 16 OC is shown in Figure 2. Test walls containing with wood framing on 16-in. centers and single top and bottom plates have a framing factor of about 14 %.

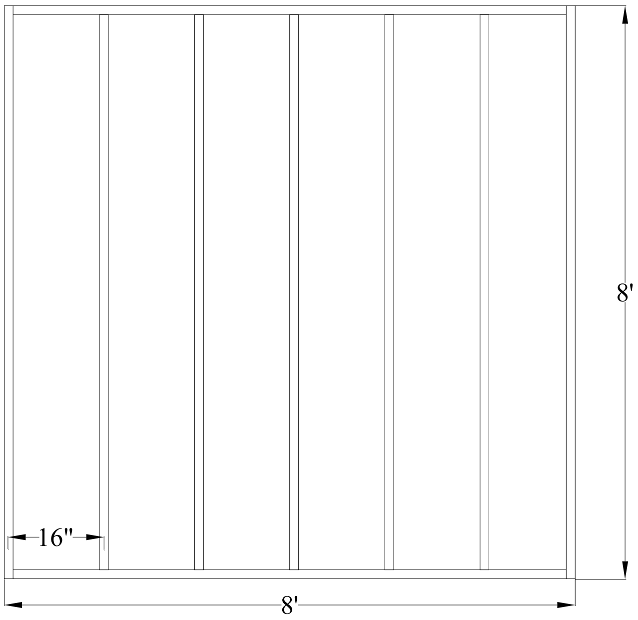

FIGURE 2. Schematic of an 8 by 8-ft. Test Wall with 16-in. Spacing

At the present time, several state energy authorities are considering incorporation of findings of the 2002 ASHRAE and CEC studies into the local energy performance requirements. Even thought, most of these codes characterize requirements for cavity insulation or R-value/U-value through the insulation, these new requirements may yield changes in material configurations of hot-box test specimens to incorporate framing factors of 25% or more. To study increased levels of framing within 8 by 8 ft test walls, six wall configurations (three wood-frame and three steel-frame walls) were analyzed to determine the effect of stud placement clear-wall R-value calculation. These configurations are shown in Figures 3, 4, and 5.

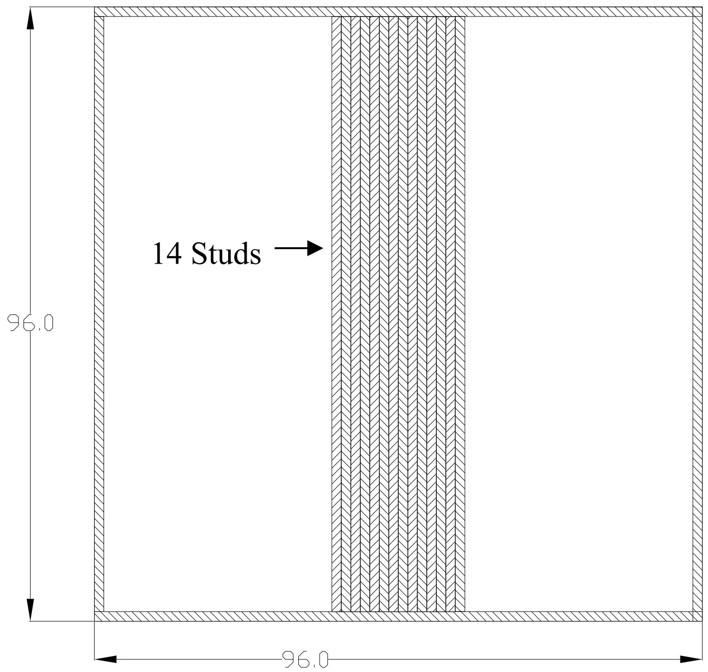

FIGURE 3. Schematic Showing Centrally Located Studs for a 27 % Framing Factor

Figure 3 shows example of the wall, where studs are centrally located. A cluster of 14 studs is located in the center of the wall. This type of configuration is common among whole-building energy modelers since it is easy to represent any framing factor by adjusting the width of a single region.

Figure 4 shows a configuration where studs are evenly distributed across the wall area. The wall shown in Figure 5 is more realistic. It contains several horizontal members, two four-stud clusters, and tow double-stud clusters. This wall configuration is probably the best representation of current structural framing practice in residential buildings of the three shown [19].

Figure 6 shows a wall configuration with 14 studs centrally located. There are 2-in. gaps between each two of centrally-located studs. This configuration was used to analyze the effects of missing insulation in areas of high concentration of structural members.

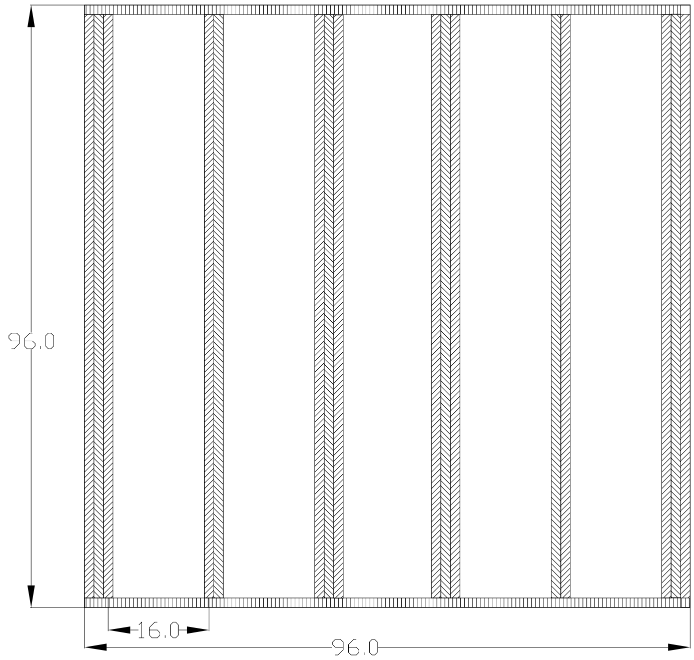

FIGURE 4. Schematic Showing Equally Distributed Studs with 16 in. OC for a 27 % Framing Factor

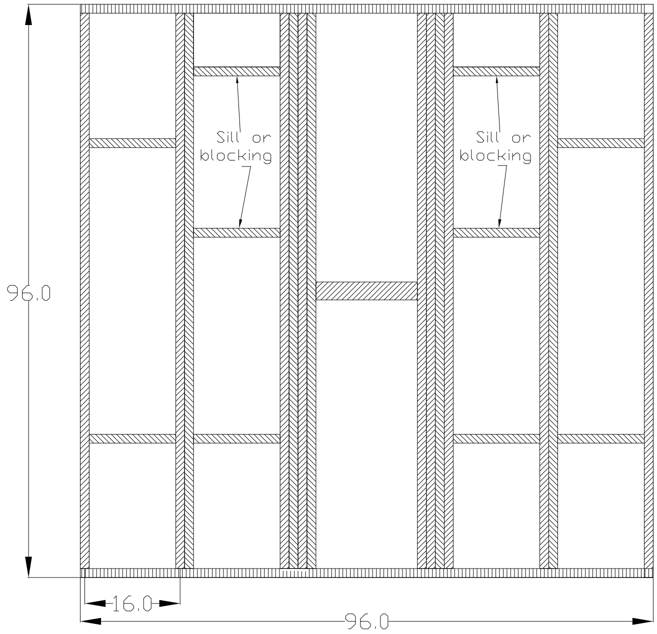

FIGURE 5. Schematic Showing a Realistic Stud Distribution with a 27% Framing Factor

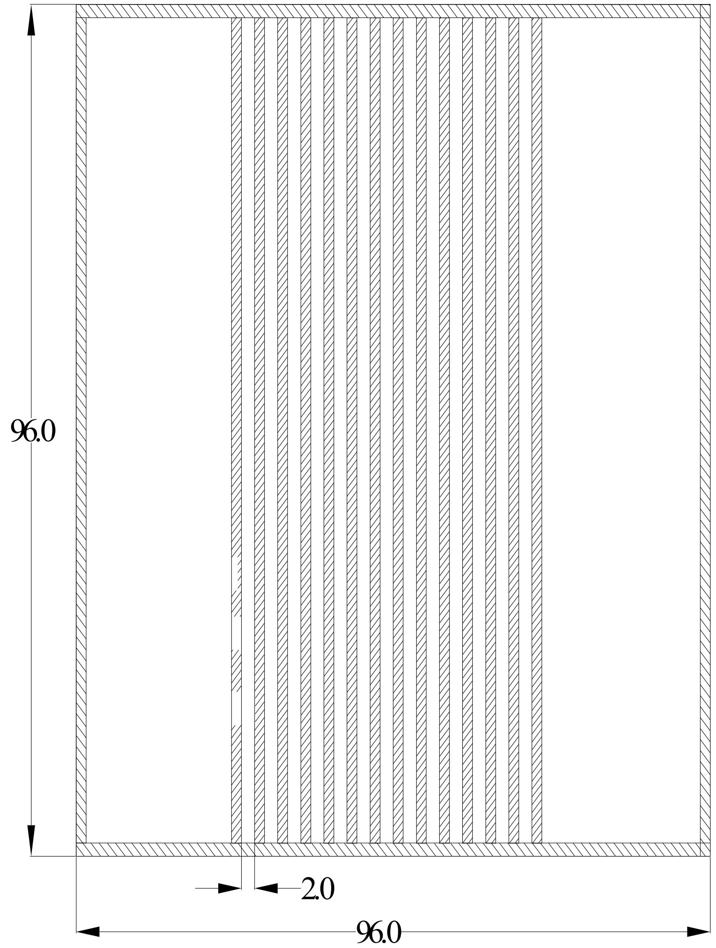

FIGURE 6. Schematic of Distributed Studs with Two-Inch Gaps and a 27% Framing Factor

To further evaluate the effect of a series of two-in. wide spaces between individual studs within a wall like that shown in Figure 6, five wall configurations (two wood-frame and three steel-frame) were studied. These configurations represented different options in installation of insulation. They are shown in Figures 7-a. through 7-e. This analysis is very important for situations where fiberglass batt insulation is in use. For small cavities fiberglass batts have to be individually measured, cut, and installed. It is a very labor-intensive process, and sometimes builders leave such small air-spaces without insulation.

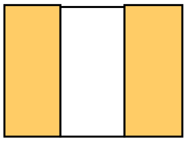

FIGURE 7.a. Wood Studs with Two-Inch Gap

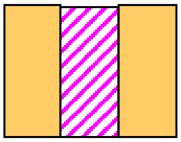

FIGURE 7.b. Wood Studs with Two-Inches of Insulation

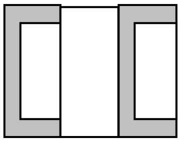

FIGURE 7.c. Steel Studs with a Two-Inch Gap

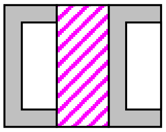

FIGURE 7.d. Steel Studs with Two-Inches of Insulation

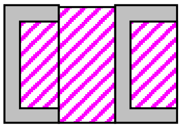

FIGURE 7.e. Steel Studs with Insulation in the Frame

In all of these wall configurations the following characteristics were maintained.

1. 27% framing factor.
2. Walls are 8 ft. by 8 ft.
3. Interior wall finish is 5/8-in. gypsum.
4. Exterior wall sheathing is 7/16-in. OSB board.
5. Wood siding is applied on the exterior side.
6. R-11 fiberglass batts are used for cavity insulation.
7. In case of wood-frame configurations, nominal 2x4 inch - 16 in. OC wood framing are used.
8. In case of steel frame configuration, conventional 3.5-in. C-shape steel studs are used with spacing 16-in. OC.

RESULTS OF COMPUTER MODELING AND DISCUSSION

A series of finite difference calculations were performed on the wall configurations pictured in Figures 3 through 7. It was observed from this analysis, that even though the percentage of framing was constant, calculated R-values varied. The following three cases were completed during the first part of the analysis.

The wall configurations were analyzed using Heating 7.3. Clear wall R-values for individual wall configurations were computed. For all of these configurations, the nominal R-value calculated for the center of cavity was R 11. The framing effect coefficients were calculated using Equation 1 and presented in Table 3 and Figure 1.

TABLE 3. R-values and Framing Effect Coefficients for Three Wall Configurations

	R-Value h·ft^2·°F/BTU		**Framing Effect Coefficent (%)**	
Type of configuration	**Wood**	**Steel**	**Wood**	**Steel**
All studs in center	9.50	5.51	26.9	57.6
Equally distributed	9.35	4.91	28.1	62.2
Equally distributed plus header and sill	9.32	4.77	28.3	63.3

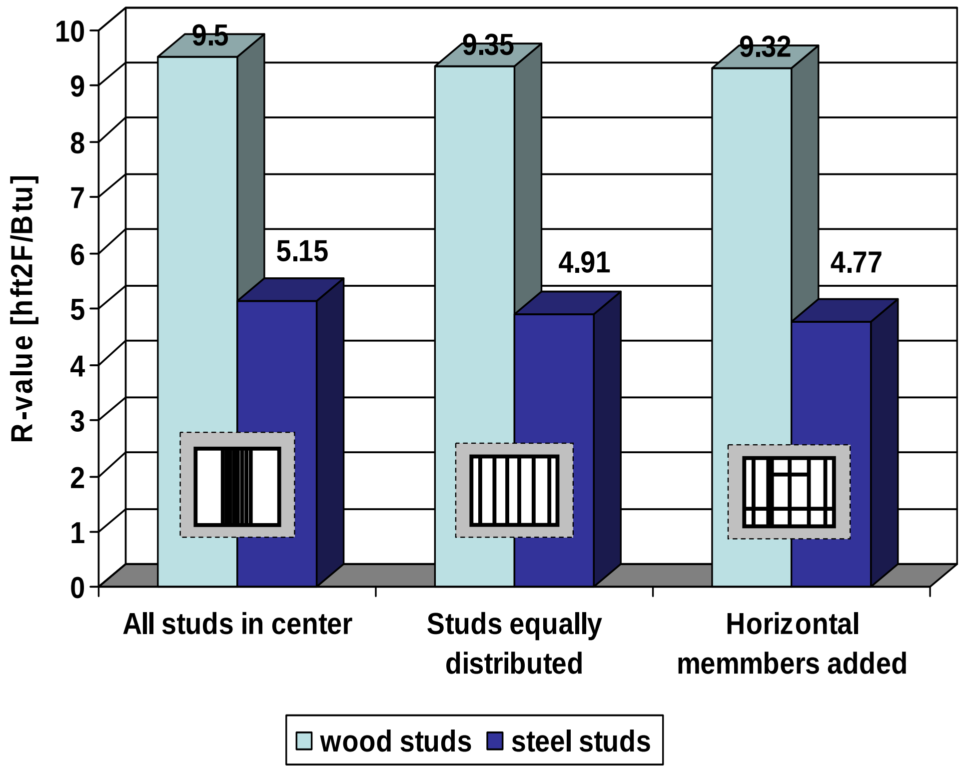

FIGURE 8. Comparison of R-values for Three Wood or Steel-Frame Walls

In the case of the wood-frame walls, the R-value variation was only 2 %. In the case of steel frame walls the variation was about 8 %. The ratio of R for the steel walls to the R for the wood walls average 0.47. The framing effect coefficient in steel-frame assemblies averaged 62 % while the wood-frame walls averaged 28 %. It can be seen from these results that a one-for-one replacement of steel for wood is not a good conservation practice. The use of steel framing should be at least combined with insulating sheathing as recommended by the American Iron and Steel Institute [19, 20].

In the case of wood-frame walls the framing factor is a good estimate of the reduction of the framing effect coefficient. This is not true in the case of the steel-frame walls because the thermal short created by the metal results in complex temperature distributions on the bounding surfaces. Wall configuration with studs in a cluster, are commonly utilized in whole-building energy simulations, due to the fact that it is very simple to represent any amount of framing. This research demonstrated that this method can be used for wood-frame walls. Unfortunately, the same rule is not true in case of steel framing, where heat transfer is more complex.

The installation of insulation in buildings is not carried out as carefully as it is done in laboratory conditions. Wall studs are often off-center by an inch or two. High concentrations of framing members create spaces where batt insulation has to be custom cut and fit. At the same time factory-made batts are not always cut precisely to fit the cavity. This problem doesn't exist when loose-fill cellulose or fiberglass insulations or sprayed foam are used.

Five additional simulations were performed to estimate the change in clear wall R-value due to the imperfections in installing cavity insulation in an assembly like that shown in Figure 6. In the first cases represented in Figure 9, small two-inch cavities between studs were empty. The second case involves two-inch regions filled with insulation – for steel studs the configuration is in Figure 7d. The third configuration reflects perfect fill of all regions in the steel-frame walls, as shown in Figure 7e.

The results presented on the Figure 9 show that wood-frame walls are very sensitive to imperfections in installation of the cavity insulation. In case of the wood stud wall containing two-inch air gaps between individual studs, the R-value was only 5.65 h·ft^2·°F/BTU**.** The framing effect coefficient for this wall configuration is 56%, which is close to that observed in steel-frame walls – see Table 3. When this gap is filled with insulation, the R-value increases to 9.24.

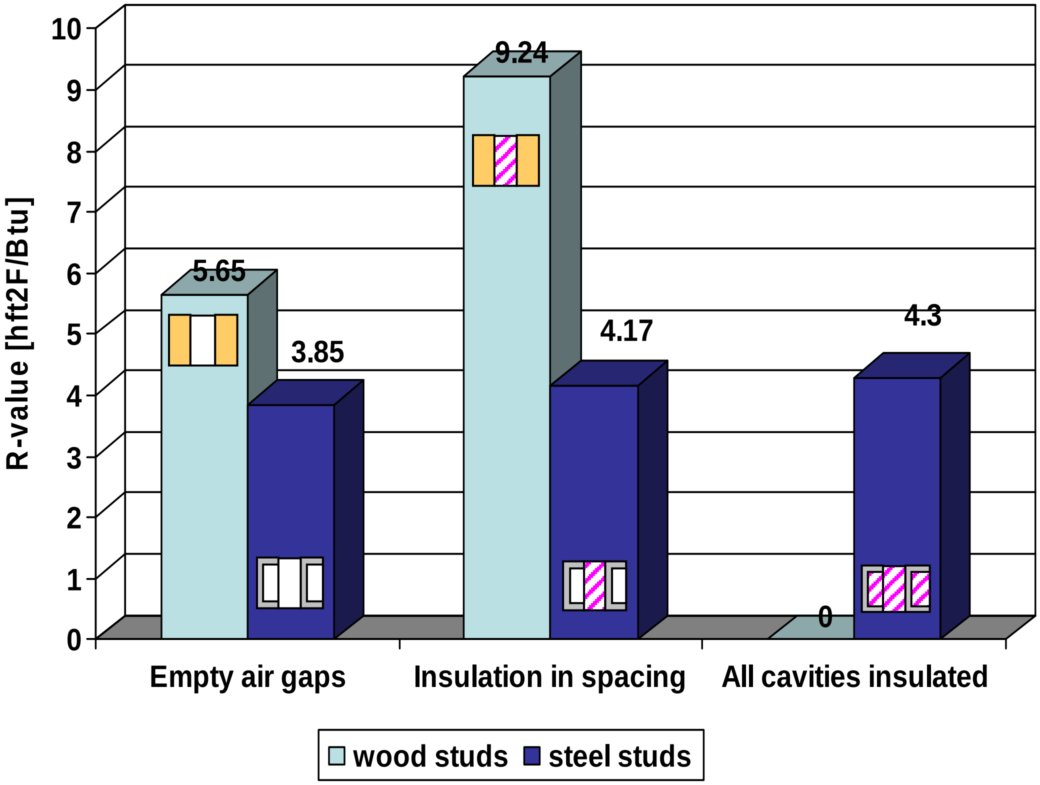

FIGURE 9. Calculated Clear-Wall R-values for Wood and Steel framing with and without Insulation Between the Studs

In the case of steel framing, the sensitivity to imperfections in insulation installation is significantly lower. In wall configuration containing un-insulated two-inch gaps between studs, the R-value is 3.85. When the gaps are partly-filled with insulation the clear-wall R-value is close to 4.17. When all of the gaps in the steel-frame wall are filled with insulation (as shown in Figure 7-e) the R-value is about 4.30 .

With the help of these five simulations we were able to demonstrate the importance of insulating the cavity carefully and correctly. Thermal performance of the wall can be dramatically changed with the presence of air gaps in stud cavities. It is good to realize that in currently-built residential houses, due to intense framing, about 30% to 40% of the wall cavities do not have precise framing and require custom cut and fit of batts insulation. Possible solutions to this problem involve application of blown-in-place cellulose, blow-in fiberglass insulation, or spray-applied foam.

CONCLUSSIONS

A series of hot-box tests and computer simulations were conducted on wall assemblies representing current residential construction practice with 24 and 27% framing factors. The following conclusions result from this research.

- Center-of-cavity R-values are significantly higher than measured clear-wall R-values.
- The addition of a ¾-in. thick expanded polystyrene foam board to steel-frame walls had a measured clear-wall R-value less than that of a similar wood-frame wall without foam-board sheathing.
- Wood-framed structures are less sensitive to differences in framing configuration then steel structures.
- Wood-frame walls are more sensitive than steel structures to imperfections in the wall-cavity insulation.
- Small air gaps between wood studs degrade wood-frame walls performance to the level of steel-frame walls.
- Thermal insulation installed in the internal areas between steel-stud flanges doesn't bring significant improvements of the steel-stud wall thermal performance.

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