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The Impact of Various Steel Stud Wall Frame Components on Energy Efficiency Analysis – Case Study

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ABSTRACT: *Steel stud framing is an excellent alternative to wood stud framing in residential construction. Steel framing is structurally sound, sustainable, and resistant to mold and insect infestation. However, the use of steel framing in the residential market remains low, due in large part to concerns on the thermal performance of steel. Over the past several years, engineers and constructors have increased the thermal resistance of steel stud walls through various wall assembly improvements, the impact of these components on energy efficiency is unclear.*

This study applies computer software to simulate the performance of various steel stud wall system assemblies. This paper also devises an E-R ratio as an index to measure the energy efficiency of various wall systems. The E-R ratios found in this study indicate that the use of either slit web metal studs or angle top tracks achieves greater energy performance than additional wall cavity insulation. This case study concludes that the most energy-efficient steel stud wall system design is achieved through the use of slit web metal studs, angle top tracks, increased cavity insulation, and optimal building orientation via sensitivity analysis. Further research needs to be conducted on steel stud assemblies and novel insulation materials to prove the economic viability of residential steel stud framing.

Keywords: simulation, steel stud wall, energy efficiency

BACKGROUND

Compared to wood stud framing, steel stud framing offers some advantages for its fundamental characteristics (ThermalSteel Corporation, 2011):

- Steel framing has proven performance in high wind load and seismic zones.
- Steel is resistant to rot, mold, termite and insect infestation.
- Steel does not emit volatile organic compounds, promoting good indoor air quality.
- Steel is “Green” because it contains a minimum of 25% recycled steel and is 100% recyclable.

In addition, the ecosystem disruption by steel production for residential steel studs is less than one percent of equivalent wood stud production (Crawford 2002). This difference of ecosystem disruption demonstrates steel’s contribution to sustainable construction for future generations.

Despite the above mentioned advantages and availability of cold-formed steel framing, basic barriers impede the residential market’s adoption of this framing. One of the barriers is how the thermal conductivity of steel stud frame affects energy performance in homes (NAHB Research Center, 2002). Steel studs form thermal bridges, causing a higher rate of heat transfer by conduction through the wall framing, leading to lower thermal resistance of steel

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stud wall systems. Most designers and builders use one or more of the following construction methods to create a thermally efficient steel stud wall system (AISI, 2003):

- Increase the fiberglass batt insulation in the wall cavity
- Increase the spacing between the steel studs
- Use an angle top track
- Use slit (slotted) web steel studs
- Add thicker rigid foam insulation to the exterior

Adding thicker rigid foam can increase the exterior insulation thickness by as much as 2 inches, which is costly and hinders siding installation.. Furthermore, several studies (Energy Design Update, 1999; Manufactured Housing Research Alliance, 2002) suggest that some of the options listed above may not be adequate to overcome the thermal bridging that steel creates in a framed wall. Therefore, it is essential that engineers and builders appropriately use the options to reduce the thermal bridging effect. However, given improvements in the technology over the past few years, the relative energy efficiency of various steel stud wall components and systems versus typical wood stud framing has remained unclear.

The objective of this study is to analyze the impact of various steel frame wall components – cavity insulation, slit web steel stud vs. solid web steel stud, angle top track vs. solid top plate – on house energy performance and find the most effective and optimal method to improve energy efficiency. A wood stud wall framed house located in Jacksonville, Florida, is selected as a case study. This research applies computer software to simulate the energy performance of the house. The simulation model is assessed by comparing the generated data to the actual energy consumption. Then the viable model is used to simulate steel stud wall framed houses with various wall component combinations. The findings from the study serve as reference for construction professionals and homeowners when assessing the use of steel stud frame in residential construction in Florida and other states in U.S. with similar climate characteristics.

INTRODUCTION TO THE CASE STUDY

Wood Wall Frame House

The house used in the modeling is a one-story, slab-on-grade, wood frame, single-family residence. This house has 2,016 square feet of living space with three bedrooms, one family room, one dining room, and a two-car garage. The average ceiling height is 10 feet, and the overall window-to-exterior wall ratio is 10%. The floor plan of the house is shown in Figure 1.

Figure 1. Floor plan of case study house in Jacksonville, Florida.

The roofs are framed using ceiling joists and rafters, decked with ½ inch nominal oriented-strand-board (OSB), and covered with asphalt fiberglass roofing shingles over felt underlayment. Wall studs are spaced at 16 inches on-center with load bearing studs located directly in line with roof rafters. All structural wood studs are 2x6 spruce pine fir cut to length. Non-structural wood studs are 2x4 spruce pine fir cut to length. Exterior walls are sheathed with 7/16 inch OSB, and finished with wood siding applied over the OSB sheathing. The details of the wall and roof frames and floor systems are listed in Table 1. The ceiling and walls are insulated with R-33 and R-13 fiberglass batt insulation, respectively. Electricity is the only utility used for cooking, heating, cooling, and other house energy demands.

Table 1
Building Envelope Details of Wood Stud Wall Frame House

Wood Frame Wall	Attic and Roof	Slab on grade
Wood stud @ 16" o.c. with solid top plates	Asphalt fiberglass roofing shingle	4" Concrete slab
Cavity Insulation R-13	1/2" wood decking	¼" Underlay cushion
Interior Drywall-1/2" Gypsum	Roof insulation R-33	3/8" Carpet
Exterior Sheathing: 7/16" OSB	Ceiling 5/8" Gypsum	Insulated perimeter
Siding Materials: Wood Siding		

Steel Wall Frame House

This study examines the impact of wall components and their thermal resistance by simulating the energy performance of various steel stud wall frame designs in homes with identical floor and roofing layouts. In the simulation, all structural steel studs are 350S162-33 mil (2x4x33 mil), and non-structural steel studs are 350S162-27 (2x4x27 mil). All metal wall studs are spaced at 24 inches on center (o.c.). Exterior walls are sheathed with 7/16 inch OSB, and wood siding is applied over OSB.

Table 2 lists five types of metal stud wall frames with varying studs, top track/plate, and cavity insulation, as well as a typical wood framed wall. The five types of steel stud wall frames are extracted from the results of experiments conducted by American Iron and Steel Institute (AISI) in 2003.

The R-values in Table 2 indicate the thermal resistances of the walls excluding wood siding. Table 2 shows that application of higher cavity insulation (comparing type III to type V), or slit web metal stud (comparing type I to type III, or type II to type IV), or angles as top track (comparing type I to II, or type III to IV) incurs higher thermal resistance of wall systems.

The authors of this paper introduce an index called E-R ratio to assess how various wall components improve energy efficiency:

$$r_{E-R} = \frac{(E_1 - E_2)/E_2}{(R_1 - R_2)/R_2} \quad \textbf{(Equation 1)}$$

where,
$r_{E\text{-}R}$: ratio of saved energy (%) to thermal resistance difference (%) between two different wall; systems (wall system 1 and wall system 2);
E_1: Energy consumption of wall system 1;
E_2: Energy consumption of wall system 2;
R_1: Thermal resistance of wall system 1;
R_2: Thermal resistance of wall system 2;

Table 2
Types of Steel and Wood Stud Wall Frames

Wall Frame Components	Types of Steel Stud Wall					Wood Stud Wall
	I	II	III	IV	V	
	R-8.9	R-9.6	R-10.4	R-11.4	R-12.2	R-12.7
Stud						
Solid Web Wood Stud						√
Solid Web Metal Stud	√	√				
Slit Web Metal Stud			√	√	√	
Cavity Insulation						
R-13	√	√	√	√		√
R-19					√	
Top Track/Plate						
Solid Track	√		√		√	√
150L150-33 Angles		√		√		
Interior Drywall - 1/2" Gypsum	√	√	√	√	√	√
Exterior Sheathing - 7/16" OSB	√	√	√	√	√	√
Siding Materials - Wood siding	√	√	√	√	√	√

METHODOLOGY

This section will discuss the methodology applied in this study, including collection of house geometric data, construction material data, energy operation data, house modeling, model assessment, and construction data.

Geometric Modeling

Computer-based simulation is accepted by many studies (Al-Homound, 2001; Lai, 2011; Waltz, 2000; and Zhu, 2006) as a tool for evaluating building energy and has been adopted in this study. There are many energy simulation programs, such as eQuest and DOE-2. The study chooses EnergyPlus as simulation tool for the following features. EnergyPlus is an energy analysis and thermal load simulation program (http://apps1.eere.energy.gov/buildings/energyplus/). While it is based on the most popular features and capabilities of eQuest and DOE-2, EnergyPlus is plugged into the Google Sketchup 3D environment through OpenStudio. OpenStudio adds EnergyPlus functionality to the Google SketchUp 3D environment, allowing users to create building geometry from

scratch, run EnergyPlus, and view the results without leaving user-friendly 3D Sketchup drawing interface.

In order to create a building model in Sketchup for the energy performance simulation, a geometric model of the house is created and then the characteristics of each modeled space (see Figure 2) are specified accordingly. The layout of the geometric model is based on the architectural plan. The geometry model of the house is first created based on the world coordinates of the house and then the model is rotated 40º clockwise according to the azimuth angle of the actual house.

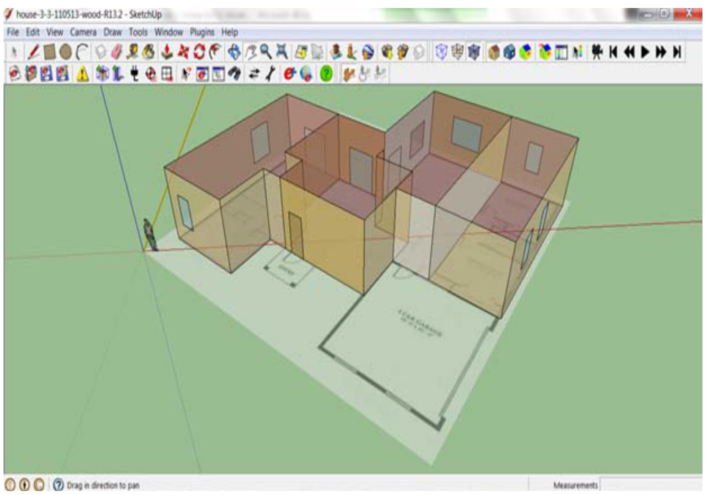

Figure 2. Sketchup 3D house model.

Construction Material and Thermal Feature Modeling

The thermal characteristics of the physical partitions of the rooms are modeled. The exterior and interior walls of the house are modeled as structural and nonstructural wall frames. Both wood frame and steel frame houses have identical roofing system, floor system, and window features for the purpose of comparison. Table 3 displays the component (wood wall frame, ceiling, and roof systems) details on the thickness, thermal conductivity, and thermal resistance. Table 4 displays the thermal conductivity and resistance of components in five metal stud wall systems.

Table 3
Construction Materials and Thermal Feature Modeling of Wood Frame House

Parameters	Thickness (in.)	Thermal Conductivity (BTU-in/h-s)	Thermal Resistance (R Value)	Total R Value
Structural wood wall frame				
Wood stud @ 16” with cavity insulation R-13			10.189	
Interior Drywall-1/2" Gypsum	0.500	1.1100	0.451	13.215
Exterior Sheathing: 7/16" OSB	0.438	0.2120	2.059	
Siding Materials: Wood Siding	0.394	0.7630	0.516	
Nonstructural wood wall frame				
1/2” Gypsum board	0.500	1.1100	0.450	
Wood wall space resistance			1.181	2.081
1/2” Gypsum board	0.500	1.1100	0.450	
Ceiling and Roof				
Asphalt fiberglass roofing shingle	0.701	0.7980	0.878	
1/2” wood decking	1.000	0.8400	1.191	35.761
Roof insulation	11.295	0.3398	33.240	
Ceiling 1/2" Gypsum	0.500	1.1100	0.451	
Floor on concrete slab				
8” Concrete slab	8.000	9.0915	0.880	2.109
Carpet and pad			1.229	
Windows				
½ ” Window	0.500	0.2614	1.913	1.913

Table 4
Construction Materials and Thermal Features of Metal Stud Wall Frames

Parameters	Thickness (in.)	Thermal Conductivity (BTU-in/h-s)	Thermal Resistance (R Value)	Type I	Type II	Type III	Type IV	Type V
Solid web metal stud @ 24” o.c. with cavity insulation R-13 and solid top track	3.823	0.599	6.375	√				
Solid web metal stud @ 24” o.c. with cavity insulation R-13 and 150L150-33 Angles top track	3.823	0.540	7.074		√			
Slit web metal stud @ 24” o.c. with cavity insulation R-13 and solid top track	3.823	0.486	7.874			√		
Slit web metal stud @ 24” o.c. with cavity insulation R-13 and 150L150-33 Angles	3.823	0.431	8.874				√	
Slit web metal stud @ 24” o.c. with cavity insulation R-19 and solid top track	3.823	0.395	9.673					√
Interior Drywall-1/2" Gypsum	0.5	1.11	0.451	√	√	√	√	√
Exterior Sheathing: 7/16" OSB	0.438	0.212	2.059	√	√	√	√	√
Siding Materials: Wood Siding	0.394	0.763	0.516	√	√	√	√	√
Total Thermal Resistance (R-value) for Wall Types				9.40	10.1	10.9	11.9	12.7

Internal Loads

The types of internal loads considered in the model include human occupants, lighting, appliances, and HVAC systems. The data is collected via owner interview. Differing weekday and weekend lighting and equipment schedules are applied to the model. Lighting appliances and other electrical appliances are simulated as lighting level parameter. The lighting level is 400 W according to the zone activity schedule and appliance power. Heating set point is 21°C (69.8°F), and the cooling set point is 24°C (75.2°F) with no setback. Ground temperature is set from 20.3°C to 23°C (68.4°F to 73.5°F).

Model Assessment

The authors compared the simulated monthly energy consumption with actual monthly energy consumption to assess the validity of the model. The actual energy consumption is collected from the homeowner for a typical year. Two sets of data are displayed in Table 5.

Table 5
Actual Energy Consumption vs. Simulated Energy Consumption

Month	Actual Energy Consumption (kWh)	Simulated Energy Consumption (kWh)
Jan	815	827
Feb	586	662
Mar	577	667
Apr	573	615
May	954	1,106
June	1,120	1,163
July	1,388	1,488
Aug	1,401	1,221
Sept	1,131	962
Oct	820	752
Nov	560	564
Dec	637	768
Total	10,533	10,795

When plotted on a graph (Figure 3), the patterns of actual versus simulated energy consumption are very similar, with slight differences occurring in the data for May, August, and September.

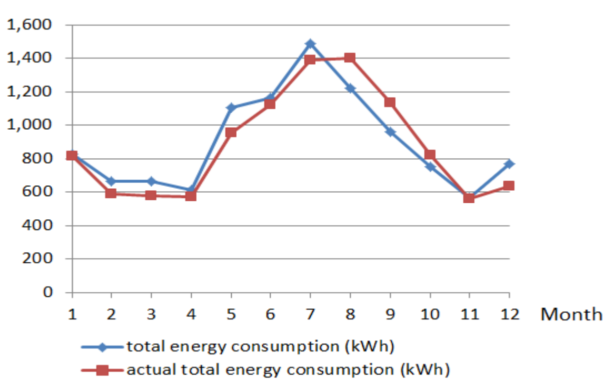

Figure 3. Actual energy consumption vs. simulated energy consumption of model house.

A statistical analysis of the data was performed using SPSS software. The results of this statistical analysis are shown in Tables 6, 7, and 8. The probability value, 0.545, labeled as "Significance (2-tailed)" in Table 6 indicates that there is no significant difference between the two data sets at the significance level of 0.0001. Meanwhile, the correlation analysis shows that these two data sets are significantly correlated (Table 7). The statistics (Table 8) also show that the means for the two data sets are very similar. The statistics analysis indicates that the model has generated viable data.

Table 6
Paired-samples t-test of actual versus simulated data of model house energy consumption

	Paired Differences					t	d.f.	Significance (2-tailed)
	Mean	Standard Deviation	Standard Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
Actual vs. simulated	-19.500	108.276	31.257	-88.295	49.295	-0.624	11	0.545

Table 7
Paired-samples correlations of actual versus simulated data of model house energy consumption

	N	Correlation	Level of Significance
Actual vs. simulated energy consumption	12	0.940	0.0001

Table 8
Paired-samples statistics of actual versus simulated data of model house energy consumption

	Mean	N	Standard Deviation	Standard Error Mean
Actual Energy Consumption	880.17	12	315.847	91.177
Simulated Energy Consumption	899.67	12	288.223	83.203

ENERGY PERFORMANCE ANALYSIS

Table 9 displays the results from simulation models for various wall systems. It shows the wood stud wall frame has the least energy consumption and it can save annual energy consumption 0.7% - 8.0%. The solid web steel stud wall system with R-9.4 consumes the most electricity. The wood stud wall frame can save up to 873kWh or $114 on an electricity bill compared to the other wall systems. Heating, ventilation, and air conditioning (HVAC) consumes over 55% of total electricity in all cases. Cooling is one of the most energy consuming categories in HVAC systems, consuming 30% of total electricity in various frame types.

Table 9
Energy Performance for Various Wall Systems of simulated model house energy consumption

Frame Type	Wall Thermal Resistance	Cost ($)	Total kWh	HVAC kWh	Cooling kWh	Fans kWh
Type I Steel	9.4	$1,517	11,667	7,409	3,603	3,192
Type II Steel	10.1	$1,489	11,452	7,273	3,513	3,063
Type III Steel	10.9	$1,461	11,241	7,140	3,427	2,941
Type IV Steel	11.9	$1,433	11,025	7,001	3,338	2,813
Type V Steel	12.7	$1,414	10,878	6,907	3,278	2,728

A regression analysis of the simulation data shown in Table 9 was performed using Microsoft Excel software. The resultant trend-line and formula of this analysis is shown in Table 9. This regression formula can be used in further studies to predict the energy performance of other wall systems with known thermal resistances and similar architectural features.

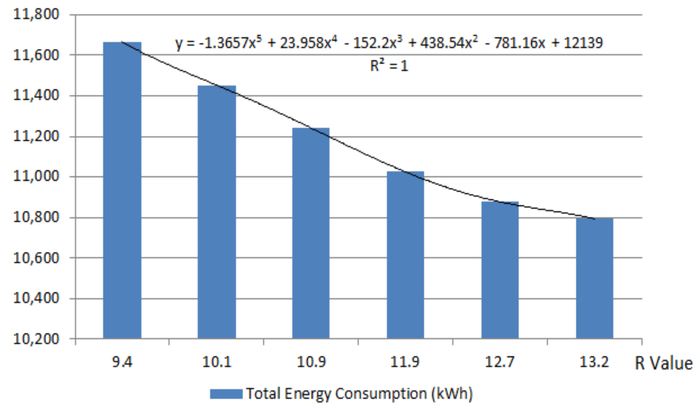

Figure 4. Energy Performance Trend-line in terms of R-value of model house total energy consumption.

Several observations are made from the simulation data:

- By comparing type I to III wall systems, the data shows slit web metal stud can save 4% energy while the thermal resistance difference between the two wall systems is 16%. The observation also applies to the type II and IV. Type IV saves 4% energy while its R-value is 18% higher than type II. The E-R ratios for the two sets of comparison are between 0.22-0.25.
- By comparing type I to II, the data indicates angle top track can save 2% energy while the thermal resistance difference between the two wall systems is 7%. This observation also applies to type III and IV. Type IV saves 2% energy while its R-value is 9% higher than type III. The E-R ratios for the two sets of comparison are between 0.22-0.28.
- By comparing type III to V, the data shows that higher cavity insulation saves 3% energy while R-value of type V is 17% higher than type III. The E-R ratio is 0.17.
- By comparing E-R ratios, the data indicates that improving cavity insulation does not save as much energy as applying angle top track or slit web metal stud.
- The optimal wall system is to apply higher cavity insulation, angle top track, and slit web metal stud.

Sensitivity analysis is conducted to minimize energy consumption by rotating the house to different angles at 30 degree increments starting from the North-South. Table 10 and Figure 5 show that the house at 180 degree from the north is the most energy-efficient. The metal stud framed house (wall thermal resistance =12.7) at this optimal angle consumes 10,225 kWh. It saves 569 kWh electricity and $74 compared to the energy consumption of the wood stud framed house at its actual azimuth angle.

Table 10
Sensitivity analysis on the wood framed house at various azimuth angles

Angles from the North	HVAC kWh	Cooling kWh	Fans kWh
(North-South) 0	10,416	3,030	2,513
30	10,763	3,241	2,650
40	10,794	3,244	2,677
60	10,525	3,019	2,630
(East-West) 90	10,688	3,155	2,661
120	10,747	3,150	2,722
150	10,369	2,902	2,594
(South-North) 180	10,152	2,836	2,444
210	10,641	3,130	2,638
240	10,711	3,150	2,686
(West-East) 270	10,777	3,272	2,630
300	10,830	3,338	2,619
330	10,552	3,113	2,566
(North-South) 360	10,416	3,030	2,513

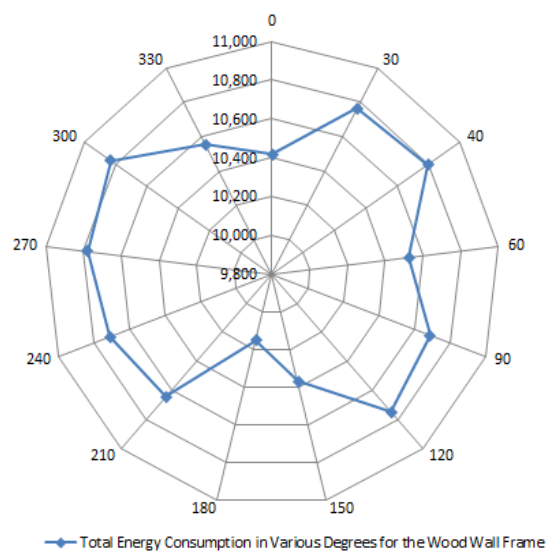

Figure 5. Total energy consumption sensitivity analysis of the wood framed house.

CONCLUSION

The study has indicated that computer-based simulation is a valuable technique to assist researchers and engineers in analyzing energy performance for various wall framing systems and material thermal features. The study models the energy consumption of a wood framed house located in Jacksonville, Florida. After assessing the validity of the model, the study uses the model to simulate various steel stud wall systems. The generated data from the simulation shows that a house built with steel stud wall frame consumes 0.7% - 8.0% more electricity than a wood stud wall frame house. Based on the data set from simulation, a trend line plotting energy consumption vs. thermal resistance is devised for this case study. The trend line predicts energy consumption of the house with known thermal resistance of walls. However, since the trend line is compiled from data of a specific house, it may limit the application to other houses without the similar architectural features. The research devises E-R ratio as an index to measure the energy efficiency of various wall system components. E-R ratios indicate that improving cavity insulation does not save as much energy as applying angle top track or slit web metal stud. The E-R ratio method is a useful index to measure other building component energy efficiency.

The ways to achieve the most energy-efficient building design and construction through wall systems is to apply higher cavity insulation, use angle top tracks, slit web metal studs, and optimal orientation of the building. In terms of construction cost, our previous study shows that a house built with steel wall frame costs 53% more than a wood wall frame house (Jiang and Zhu, 2011). Wood stud wall frame costs $14,288 compared to steel stud wall frame which costs $21,870 (Jiang and Zhu, 2011). Therefore, providing both thermally efficient and economically viable steel stud wall is a challenge for engineers and construction contractors. Although steel stud is a more structurally sound and sustainable material, construction cost has to be reduced to make the material more competitive and affordable. This research provides alternatives to achieve energy efficient steel stud wall design and construction, but further research should be conducted to study the impact on energy performance and construction costs by modifying steel stud spacing, new insulation materials, and new construction techniques.

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